

UNIVERSITY OF CAPE TOWN

DESIGN AND CONTROL
OF
EQUALIZATION TANKS

by

P.L.Dold, B.Sc. (Eng.)(Cape Town)

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Department of Civil Engineering,
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I, Peter Dold, hereby declare that this thesis is my own work and that it has not been submitted for a degree at another University.


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SYNOPSIS

The objective of this investigation was to develop a control strategy for the operation of an equalization tank upstream of a wastewater treatment plant which utilizes the available equalization hold-up volume in such a manner that it reduces, optimally, diurnal fluctuations in both influent flow and load rates.*

The influent to a wastewater treatment plant generally exhibits wide diurnal variations in both flow rate and concentration, and consequently in load rate (defined as the product of flow rate and concentration). Deviations of these parameters from steady state cause plant operating problems in areas such as aeration control (due to load rate fluctuations), settling tank overloading (due to flow rate fluctuations) and/or over- or under-aeration which affects settling properties, and others. Adverse effects of both flow and load rate fluctuations can be minimized either by (1) suitable in-plant control, or (2) installing an equalization (or balancing) tank upstream of the plant.

In-plant Control: In the application of in-plant control, problems are encountered particularly in the South African context. Effective control of nutrient removal processes (which include anaerobic, anoxic and aerobic zones) requires (i) sophisticated models for the kinetics of the activated sludge process and the settling tank behaviour - it is doubtful whether an adequate model exists as yet; and (ii) sophisticated monitoring equipment - in many areas of South Africa the technical infrastructure and manpower requirements, necessary to maintain a sophisticated in-plant control system,

* The selection of load, instead of concentration, as a parameter to be equalized, requires some comment. The selection is justified from the kinetic behaviour of the activated sludge process. In terms of the process model developed by Dold, Ekama and Marais (1980), at long sludge ages process response is controlled principally by the variation in load rate (i.e. concentration x flow rate), not by the variation in concentration alone.

are not available. For the above two reasons it was deemed that in-plant control of nutrient removal processes in South Africa was simply not feasible. In addition, even if in-plant control under the cyclic inputs of flow and load was successful, the level of process performance attainable would still not be as high as that which can be attained when a plant is operated under constant inputs. For example, the efficiency of nitrification under cyclic conditions can never be as high as that observed under constant inputs as a consequence of the process kinetics. These considerations provided the motivation for enquiring into the second approach to control of wastewater treatment plants.

Equalization: From a theoretical viewpoint, complete or near-complete equalization of both flow and load would either eliminate the need for in-plant control or reduce the required in-plant control to the simplest level, within the competence of the plant operator. In addition to providing a solution for the control problem, equalization can reduce plant capital costs; for example, (1) aeration capacity to be provided will be determined essentially by the mean influent COD load instead of the peak load, (2) settling tank areas can be reduced to cope with the mean inflow rate, and not the peak flow rate.

Two main features have detracted from equalization as a method for controlling treatment plant operation:

- (1) Traditionally the objective in operating an equalization basin was to attenuate *flow rate* variations. Little emphasis was placed on the deliberate attenuation of load rate variations; the degree of load attenuation that automatically accompanies flow equalization was considered rather as a secondary bonus^{*} - equalization, as practiced

* The primary interest in *flow* equalization alone is understandable: Flow equalization generally was tested only on plants operated at short sludge ages (< 3 days). From kinetic considerations, the response of parameters such as oxygen utilization rate is largely attenuated in this situation; therefore the need for *load* equalization is not as crucial as for plants operated at long sludge ages where these parameters respond sensitively to influent load rate variations. That is, flow equalization sufficed in overcoming the operating problems.

in the past, does not necessarily supply an effective control tool because, even where flow equalization is accomplished, the associated degree of load equalization might not be sufficient to overcome the control problems arising from load rate fluctuations.

- (2) Difficulties have been encountered in the successful operation of flow equalization facilities. Operational procedures reduce to setting the tank outflow rate each day on the basis of an estimate (by the plant operator) of the expected inflow over the ensuing 24-hour cycle. This approach can, at best, be described as only moderately successful: because the inflow is seldom constant from day to day, particularly between weekday and weekend, the approach relies heavily on operator ingenuity and experience. That is, flow equalization has suffered from a lack of an efficient operational strategy.

With the advent of low-cost microcomputers it was considered feasible to devise an on line control strategy that will (1) minimize diurnal deviations in *both* flow and load rates from their respective mean values within the volume constraints of the particular system on a continuous basis, and (2) overcome the difficulties inherent with operation of equalization facilities by human agency. Development of this control strategy was the principal objective of this thesis.

REQUIREMENTS FOR CONTROL

The essence of the control problem in equalization is to determine, for a specified installation, under the daily cyclic inputs of flow and load, the appropriate tank outflow rate at any instant so that variations in both the flow and load rates are optimally minimized, yet ensuring that the equalization tank neither overflows nor empties over the daily cycle.

To solve the control problem, the approach adopted in this investigation was to *predict* influent flow rate and concentration (and hence load rate) patterns over the ensuing 24-hour period; then *compute* the outflow profile (for the ensuing 24-hour cycle) that gives the least error in terms of some flow and load optimization criterion.

The first portion of the outflow rate profile specifies the optimal outflow rate for an ensuing short interval (of, say, half an hour). By repeating this procedure at regular short intervals, to account for differences between actual and predicted inputs, operation of the equalization facility is optimized continuously.* Attainment of these objectives devolved into seeking solutions to two questions:

1. If the complete influent flow rate and concentration patterns for a 24-hour cycle are known, how is the outflow rate pattern for optimal equalization determined? The solution to this problem requires the development of an *equalization algorithm*.
2. If the influent flow rate and concentration patterns and the mean flow and mean load per day are not constant from day to day, how are the influent patterns to be predicted, and how is this variability accommodated to achieve real-time optimal equalization? The solution to this problem requires application of the equalization algorithm in an appropriate *control strategy*.

EQUALIZATION ALGORITHM

The solution to the first problem involves the application of an equalization algorithm by means of which, given a specified influent flow rate and concentration pattern and a specified size of equalization tank, successive incremental adjustments are made to an initial outflow pattern until the resultant pattern, when considered with the associated effluent load rate pattern, yields optimal equalization of flow and load. The optimal condition is identified by minimizing an empirical error function that expresses the integrated daily deviation of both flow and load rates from their respective mean values. The relative importance of flow as against load equalization may be varied through applying a weighting factor, α , to the errors for flow, E_f , and load, E_{ld} , respectively, as shown in Eq (1):

* This approach is very different from the traditional one where the objective, theoretically at least, was to accept some fixed daily cyclic influent flow rate pattern and determine the tank volume required to allow the tank outflow rate to be held constant equal to the mean inflow rate. In contrast, the approach here is to accept the tank volume and then to control the outflow rate to give the minimum deviation from the mean; that is, the approach makes allowance for variability in the daily cyclic influent pattern - a feature observed in practice and which leads to problems in applying the traditional method. Therefore, even if the available volume is too small to allow complete equalization, that volume is utilized optimally.

$$E_e = \alpha E_f + (1-\alpha)E_{ld} \quad (1)$$

where

E_e = total equalization error due to flow and load rate fluctuations.

An implicit part of the general optimization problem involves ensuring that, under the specified input of flow over the day, the optimal outflow pattern gives rise to a tank hold-up (or volume) profile which at no time exceeds specified upper and lower volume limits. Satisfaction of this constraint was resolved by introducing a penalty error, E_{lm} , that increases rapidly as the tank hold-up attains values outside of the specified limits. This ensures the development of an optimal tank outflow rate profile that, under the 24-hour inflow rate pattern, results in an associated tank hold-up profile over the day which does not exceed the specified tank hold-up limits of the selected equalization tank.

The combined effect of the equalization error and the penalty error for volumetric limits introduced a further problem: "spikiness" in the 24-hour tank outflow profile could develop when the tank was near full or empty, particularly for tank retention times of less than 3 hours (based on the mean inflow rate). This problem in the optimization procedure was resolved by incorporating a second penalty error, E_s , to constrain the rate of change of the tank outflow rate. This penalty has an additional benefit; rapid changes in the outflow rate profile not adequately reflected in the equalization error are damped. Consequently, the total error, E_t , used as the objective function in the optimization procedure consists of three components:

$$E_t = E_e + E_{lm} + E_s \quad (2)$$

The equalization algorithm, once established, was used to assess the effects of various relevant parameters such as configuration, size, etc. on equalization performance. For this analysis, to compare the different equalization results on a general basis, a measure of the equalization efficiency was required. This was provided by a *relative error*, E_r , defined as the ratio of the equalization facility effluent equalization error (Eq 1) to the influent stream equalization error (also calculated from Eq 1, but utilizing the influent flow and load

rate patterns). The analysis was carried out assuming fixed daily cyclic influent flow and load rate patterns that closely approximated those encountered at full-scale wastewater treatment plants and covered the following aspects:

1. In-line equalization was analyzed with regard to (i) equalization tank retention time; (ii) the form of the influent flow rate and mass loading patterns; and (iii) the equalization error weighting factor, α , (see Eq 1).
2. Side-line equalization (with flow division either by "splitting" or "topping") was analyzed with regard to (i) equalization tank retention time; and (ii) the value of the flow division factor.

The analysis provided certain useful guide-lines for the design of equalization facilities; from the results it was found that:

- The efficiency of equalization improves with increasing tank size: however, the *rate* of improvement decreases with increasing tank size. Optimal equalization requires a tank with a mean retention time in the region of 4 to 6 hours; little is gained in equalization efficiency for retention times greater than 6 hours.
- A reduction in excess of 90 percent on flow and load rate fluctuations can be obtained with a tank retention time of 4 to 6 hours.
- In the region of effective equalization, whereas the uncontrolled load rate in the influent cycle may fluctuate between one quarter and four to five times the mean (with consequential low and high oxygen demands in the downstream process), the equalized load rate remains virtually constant, with a small *drop* once every 24 hours. This behaviour will simplify aeration rate control considerably, and bring about a substantial reduction in the aeration capacity required to match the peak load rate - a factor of particular importance for processes operated at long sludge ages.
- Comparison of in-line and side-line equalization indicates that, in the region where effective equalization is achieved,

neither scheme results in a reduced tank volume requirement over the other. Side-line equalization, however, has one adverse feature in practice; rapid, random variations in the influent flow and load rate patterns will be transmitted in part to the downstream process in the stream bypassing the balancing tank. (With in-line equalization the tank acts as a buffer for these variations).

- The only motivation for utilizing side-line in preference to in-line equalization is a possible saving in pumping costs in situations where gravity flow to and from the equalization tank is not possible - results of the study under fixed input patterns show that as much as 60 percent of the influent flow can bypass the equalization tank with only a marginal reduction in equalization efficiency.

CONTROL STRATEGY

In real-time operation the daily cyclic influent patterns change from day to day both in the form of the patterns and the mean daily input values. Incorporation of the equalization algorithm in a control strategy for the real-time, continuous operation of an equalization facility involves the prediction, at any point in time, of the expected influent patterns for the ensuing 24-hour cycle. The prediction is based primarily on historical inflow and concentration data, but also incorporates differences between actual and historical inflow rates for the period prior to the prediction. Historical data is stored in the computer memory, and is continually updated as and when information is available.

For application of the control strategy, the day is divided into a number of, say, half-hour control intervals. At the beginning of an interval, the expected influent patterns for the ensuing 24-hour cycle are set up and utilized by the equalization algorithm to compute the optimal simulated tank outflow profile for the 24 hours ahead. The outflow value determined for the first interval in the 24-hour cycle is then applied as the actual output for the duration of that interval. By repeating this procedure at the start of each control interval (i.e. every half-hour in this case) performance of the equalization tank is continuously optimized.

An important aspect of the control strategy is that the algorithm differentiates between influent patterns for weekdays and weekend days. From a comparison of data collected at several treatment plants in South Africa it was apparent that the influent patterns for weekdays and weekend days differ sharply in (1) the forms of the flow and load rate patterns, and more important, (2) a reduction (of approximately 30 percent) in the mean daily influent flow and load rates from week to weekend. By distinguishing between the two types of pattern, the strategy optimally reduces the effect of the transition from week to weekend, and *vice versa*.

The control strategy was tested by simulation of the controlled equalization tank response under a wide range of influent conditions using both (1) influent data measured on full-scale treatment plants and (2) unusual inputs (e.g. simulated storm patterns) so as to stress the strategy to the extreme. By comparing response under real-time inputs with invariant inputs it was also possible to check whether the conclusions regarding equalization performance obtained under fixed diurnal input patterns also hold true under real-time inputs. In all cases the conclusions (with regard to tank size, configuration, etc) obtained under fixed diurnal input patterns were found to hold under real-time inputs.

IMPLEMENTATION

Once the control strategy had been tested successfully in simulations, the scheme was implemented at full-scale on the 100 Ml.d⁻¹ Goudkoppies wastewater treatment plant at Johannesburg; this plant has a 22 750 m³ in-line equalization tank (i.e. approximately 5,5 hour mean retention time). In this instance it was possible only to test the flow equalizing aspect of the strategy (i.e. $\alpha = 1,0$ in Eq 1) because there was no mechanical mixing of the tank contents.

The requirements for implementing the strategy at Goudkoppies, in addition to the microcomputer, were the facility (1) to measure tank outflow rate and tank level, and transfer these measurements to the microcomputer, and (2) to specify the setpoints for the tank outflow rate controllers from the microcomputer. An interface for conditioning the signals passing between the microcomputer and the plant was designed and manufactured at the University of Cape Town.

The principal requirement for optimal real-time operation is that the historical inflow rate data stored in the microcomputer memory approximates the actual inflow rate pattern with reasonable accuracy. Two features helped to ensure this requirement:

1. The strategy differentiates between the two characteristic types of influent pattern - for weekdays and weekend days.
2. The strategy is self-correcting: over the first few days of operation, if the historical inflow rate data initially stored in the microcomputer memory does not reflect the actual inflow patterns accurately, the strategy response is not optimal. However, the strategy automatically updates the historical data on the basis of the observed inflow rates. By means of this updating mechanism, the strategy ensures the development, after a few days, of a running average historical daily influent pattern close to the respective observed patterns during the week and over the weekends. In addition, the effect of seasonal changes in the inflow patterns is automatically updated in the patterns.

Had the objective at Goudkoppies been implementation of the control strategy with both *flow and load* equalization (i.e. if the tank contents were mixed) it would appear that continuous monitoring of COD concentration would also be required. This would pose a problem because both the instrumentation to monitor COD on a continuous basis, and the operation thereof, are complex and costly - this would nullify, to a degree, the objective of developing a low-cost simple alternative to in-plant control. However, continuous monitoring of COD concentration is not demanded; it is sufficient to check the historical COD data stored in the microcomputer memory at intervals of, say, 3 months. This is so because simulation studies indicate that the system response is relatively insensitive to deviations in actual influent concentration from the historical data. The reason for the insensitivity arises from the fact that the load rate is the product of the flow rate and concentration; because the flow rate is accurately accounted for continuously, deviations in concentration affect the load value only in part. Indeed, the added efficiency to be obtained by continuous COD monitoring is unlikely to merit the cost of implementation.

Under the control strategy the efficiency of equalization at the Goudkoppies plant was far superior to that attained prior to the implementation when the tank outflow rate had been manually specified, and the strategy operated very effectively:

- The tank outflow rate was held very close to the optimum indicated by the simulations and the analysis under fixed diurnal inputs. During the midweek period the tank outflow rate was maintained very near constant. The strategy also smoothed the transition from week to weekend, and *vice versa*, by spreading the effect of the step change in daily inflow over an extended period.
- The on-line strategy removed a considerable work load from the plant operators, and relieved the operators of a difficult and frustrating task.
- The level of equalization efficiency was incomparably higher than that attained when the outflow rate was specified manually. For example, problems of tank overflow were no longer encountered - this had been a regular occurrence under manual operation.

In the case of the un-mixed Goudkoppies equalization tank receiving settled sewage, a limited study has shown that the degree of equalization of *load* is very close to that indicated by simulations for completely mixed tanks. This observation, however, should not be taken to mean that mixing is not required - it may be a result peculiar to the design of this specific tank.

The only problem encountered in the operation of the control strategy at Goudkoppies has been damage, on one occasion, to electronic equipment as a result of lightning strikes in the vicinity of the plant. It would appear obligatory to include protection against lightning damage at locations where electric storms are of common occurrence.

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CHAPTER ONE

INTRODUCTION

The influent to a wastewater treatment plant (WWTP) usually exhibits a wide diurnal cyclic variation, both in flow rate and concentration (COD, TKN), and consequently in load rate (defined as the product of flow rate and concentration). The form of the input patterns to a particular plant are determined by a number of factors such as population structure; sewer layout, lengths and gradients; climatic and seasonal effects; etc. However, despite the many influencing factors, generally it is found that the combined effect gives rise to influent flow and load rate patterns that are similar for most plants. Typically the flow rate reaches a maximum, at some time during the day, of about two times the average daily rate, and a minimum sometime during the night of about half the average rate. The influent COD and TKN concentrations show a similar pattern of behaviour, virtually in phase with the flow variations. As a result the diurnal cyclic load rate variation can range from four to six times to less than a quarter of the average daily value.

Daily cyclic variations in flow and load rates affect the design, performance, and operation of wastewater treatment plants, principally as follows:

- Design: The effect of variable input patterns on plant design generally is one of increased capital costs; for example:
- (i) The settling tanks and hydraulic connections must be designed to cope with the peak flow rate
 - (ii) The aeration capacity must be designed to cope with the peak oxygenation rate requirement set by the peak load rate.

Performance: Peak loads and flows may cause "overloading" of the reactive capacity of the organism mass or the physical design provisions; as a result there may be:

- (i) "Leakage" of pollutant to the effluent; this effect is particularly noticable in nitrifying plants where cyclic flow and load variations virtually always have a deleterious effect on the conversion of ammonia to nitrate.
- (ii) Inadequate oxygenation during peak load periods; this may cause a sharp deterioration in nitrification efficiency, and promote the growth of undesirable organism types that adversely affect the settling properties of the mixed liquor.
- (iii) Partial or total failure of the settling tanks under peak flow rates, a problem often compounded by deterioration of settling properties due to (ii) above.

Operation: Diurnal cyclic variations in load rate necessitate that the aeration rate be adjusted accordingly, to limit over-aeration and to prevent under-aeration. Over-aeration constitutes a wastage of energy and may affect liquid/solid separation and clarification efficiency in the secondary settler, whereas under-aeration may promote the growth of undesirable organisms again to cause settling problems, as stated earlier.

1. DEVELOPMENT AND APPLICATION OF WWTP CONTROL PROCEDURES

Attempts at resolving the difficulties encountered in activated sludge plant performance and operation due to the cyclic nature of the inputs of flow and load have led to wide interest in the development and the application of control procedures for treatment plant operation.

Generally, two philosophies towards a solution of the problem have achieved prominence; namely:

- (1) In-plant control, wherein no attempt is made to attenuate variations in influent flow and load rate, but each treatment unit is controlled separately in such a way that the effects of the cyclic inputs are adequately accommodated.
- (2) Equalization control, wherein the influent flow and load rates are regulated to relatively constant values upstream of the biological process, thereby simplifying and/or reducing the control requirements within the plant.

2. IN-PLANT CONTROL

2.1 General Considerations

In-plant control procedures, or strategies, have existed in some measure for many years. Initially these procedures probably developed from a commonsense evaluation of plant behaviour to enhance plant performance or to accommodate a crisis condition. For example, the step feed procedure evolved to accommodate peak loads along the length of a semi-plug flow reactor in such a manner that the aeration capacity could be effectively utilized over the plant. A second example is that of aeration control which probably also was developed to save on aeration costs and to improve plant performance with regard to, say, settling behaviour. Initially the strategy probably was based on simple chemical dissolved oxygen tests (e.g. Winkler titrations), to develop a schedule for switching parts of the aeration system in and out to maintain a reasonable oxygen concentration. Development of dissolved oxygen meters greatly promoted this form of control.

Although empirical, many in-plant control procedures in the past have been applied with reasonable success in practice, but with heavy reliance on operator participation. Effective manual application of control strategies requires operator ingenuity, good understanding of the way a plant responds to flow and load variations, and almost continuous attendance at the plant; these impose a heavy responsibility on the operator. In general these operator requirements can be assured only at large plants - on small plants usually there is neither the manpower available nor the competence to implement any strategy beyond even the most elementary kind.

To overcome the problems associated with manual application of control strategies, automation of these strategies has become a topic of worldwide interest. The interest in automation of treatment plants is reflected in the large number of published papers and international workshops directed specifically towards the study of Instrumentation, Control and Automation (ICA) equipment systems (e.g. IAWPR international workshops held in London, Stockholm and Munich). As a result of these studies there has come the realization that installation of

automatic controls will have a number of benefits not restricted to improved plant performance only. For example, an in-depth study sponsored by the U.K. Department of Industry (which resulted in the ERL Report) identifies, *inter alia*, the following benefits accruing from investment in ICA systems (Drake and Page, 1981):

- Improved quality control
- Savings in energy consumption
- Improved service
- Improved operating flexibility
- Reduction in dirty jobs and inconvenient working hours
- Improved repair and maintenance information
- Better use of existing facilities.

Automatic control has been made possible only in recent years by the development of more sophisticated monitoring instruments and automatic control equipment. This, in turn, has resulted in an increased level of sophistication in the control procedures. Taking the example of aeration control again, initially this involved adjusting aeration rate on the basis of dissolved oxygen concentration measurements; more recently instrumentation has allowed the development of control strategies which utilize both dissolved oxygen concentration and oxygen utilization rate measurements as control parameters.

The one item of equipment which has made the largest impact on the approach to development of wastewater treatment plant (and other process) control procedures is the low-cost microprocessor-microcomputer. The availability of computational facilities has channelled the approach to control towards development of "intelligent" control strategies where control action is taken according to predictions of process response based on the utilization of a computer model to simulate process behaviour.

In the field of wastewater treatment, successful application of such computer-based control strategies has been limited by two factors in particular:

- (a) A lack of reliable models describing the dynamic behaviour of the activated sludge process (and that of other unit processes such as settling tanks).
- (b) Deficiencies in the long-term reliability of the instruments monitoring the parameters necessary for implementing the strategies.

(1) Process Model Development: From a theoretical point of view an essential requirement for the development of an effective in-plant control strategy is a reliable model describing both the treatment process and the settling tank behaviour under dynamic flow and load conditions, for any process type and configuration (e.g. nitrification/denitrification/phosphorus removal systems). A number of models have been developed for the various unit processes, and have been evaluated with a certain degree of success. It is probably not wrong to say that a predominance of the more sophisticated strategies for the control of the activated sludge process under dynamic input conditions have been based on relatively unsophisticated process models and simple process configurations. Such strategies may be adequate for certain applications such as control of single reactor aerobic systems where reduction of COD load only is the objective; typically these systems are operated at very short sludge ages (<2 days) - in this situation the response of the process under variable input conditions largely is damped, thereby simplifying the control problem considerably. However, it is likely that strategies based on oversimplified process models will be inadequate if extended to the control of more complex processes, for example, nutrient removal processes that include anaerobic, anoxic and aerobic zones; the interaction of the various subsections of the process necessitates a fairly complex process kinetic model for adequate control strategy performance. In consequence, the validity of any control strategy suited for wide application will depend in a large measure on the validity of the theoretical model; this is an aspect on which it is difficult as yet to give a pronouncement.

(2) Monitoring Instrumentation: The second problem in the application of in-plant control relates to the reliability of monitoring instruments; as yet problems in this regard are real, making this an important factor to be considered in deciding whether a plant is to be automated or not. Certainly, automation is not to be thought of if the technical support and infrastructure is not available to provide the necessary back-up services to maintain a range of measuring and control instruments. In South Africa, except for the metropolitan areas (perhaps), inadequate support will be the rule rather than the exception.

2.2 Implications for South Africa

At present a major dilemma faces the plant designer in South Africa. In order to meet stringent effluent quality regulations advanced activated sludge processes to accomplish nitrogen and phosphorus removal have become commonplace in South Africa; such plants are being proposed and built to serve communities ranging from the larger urban to the smaller rural ones. For continuous successful operation, these plants require more stringent control than the normal aerobic plants. From an automation point of view, under cyclic flow and load conditions the monitoring instrumentation required on these multi-reactor systems will be even more elaborate than for aerobic plants. Furthermore, any strategy to optimize the attainment of the plant objectives will be complex and to date such a strategy has not been developed, not even theoretically. Even when such a strategy is forthcoming, servicing of measuring instruments and the provision of adequate back-up services will remain a major problem in South Africa for the reasons outlined in the previous Section; it is indeed difficult even to envisage, at this time, the successful application of in-plant automation of nitrogen and phosphorus removal plants on a nationwide basis.

Recognizing the difficulties associated with in-plant automated control under cyclic inputs of flow and load, attention has been directed to the alternative solution to the problem - equalization of flow and load rates prior to discharge to the plant.

3. EQUALIZATION APPROACH TO CONTROL

A means for overcoming, or bypassing the problems involved in the development and application of in-plant control procedures would be to regulate the influent flow and load rates to relatively constant values upstream of the plant i.e. *equalization* of flow and load. The principal advantages of this approach (over that of in-plant control) are: (1) the measure of control still necessary in the process can be performed by manual means at infrequent intervals (or by using simple equipment); and (2) the requirements for sophisticated monitoring equipment, accurate kinetic models of the process and settling tank behaviour, and high levels of operator expertise, will fall away. In addition it is accepted generally, that constant inputs of flow and load should lead to improved process performance over that which at best can be attained under cyclic conditions and, that optimization of process performance should be simplified considerably.

The equalization approach does not eliminate the need for control; however, a brief consideration of the general requirements for application of the equalization control approach does indicate that this method will be more simple to apply than an in-plant control procedure: application of this method most likely will revolve around flow rate measurement and regulation of flow rate - procedures which can be applied with simple instrumentation and equipment, and have been operated effectively and reliably in a wide range of process applications over many years.

3.1 Methods for Implementing Equalization

Any equalization method necessarily must involve the principle of retaining flow (and load) during peak periods, and distributing the stored flow (and load) at times during the cycle when the actual inputs drop below the mean daily values; in this manner, the flow and load rates passing to the biological process are maintained as close as possible to the respective mean values. One means of achieving this has been to utilize the hold-up capacity of the sewer system, and then regulating the pumping rate to the plant appropriately. This approach has three principal drawbacks:

- Implementation most likely will involve extensive modifications to the sewer system; for example, underground sumps and pumping installations probably will be required at a number of points in the sewer network.
- There are difficulties in providing a generalized system for widespread application because many of the problems will be specific to particular situations.
- The effective working life of such a system could be affected dramatically by, say, housing or factory development along the sewer network.

The most logical method for implementing an equalization scheme appears to be the installation of a holding tank (generally referred to as a balancing, or equalization tank or basin) at the treatment plant, upstream of the biological process. Allowing the cyclic input of flow and load to enter the tank, it should be possible to attenuate fluctuations in both flow and load to a considerable degree by regulating the flow from the holding tank, thereby reducing the requirements for control within the plant needed to achieve satisfactory operation.

A number of full-scale treatment plants have incorporated equalization tanks in the inflow circuit (EPA, 1974; Ongerth, 1979). Generally the objective in including these tanks in plant design has been to reduce the daily cyclic fluctuations in the influent *flow rate* to reduce problems stemming from variations in the hydraulic flow through the plant. With flow equalization the hold-up provided in the equalization tank necessarily induces some attenuation of the influent *load* variations. However, the load equalization aspect has been viewed as a secondary objective only, in the nature of a benefit consequential to flow equalization rather than as an end in itself. Nevertheless, flow equalization with its associated degree of load equalization should have substantial benefits in terms of plant performance and operation. Examples of specific benefits which should accrue from flow equalization, and which have been quoted in the literature, are:

- Improved performance of secondary settling tanks due to

more constant solids loading.

- Improved biological process performance through a partial reduction in food/micro-organism loading peaks.
- Simplified control of in-plant flow rate dependent operations such as chemical dosing and recycle pumping.
- Simplified control of aeration rate due to attenuation of influent load rate variations.

It would appear from the above list that flow equalization can only have positive consequences. However, studies on the effect of flow equalization on plant operation and performance have led to conflicting conclusions. Some studies report both improved performance and simplified operation; others, analyzing the performance of plants operated under equalized and unequalized flow conditions, have concluded that there is little, or no benefit to be derived from the inclusion of an equalization tank in the system - a conclusion which contrasts sharply with that indicated from the theoretical analysis of plant performance under constant and cyclic flow conditions. In order to evaluate and/or explain these conflicting opinions on the merits of flow equalization, it is necessary to enquire critically into the basis on which the conclusions were formulated. This will be dealt with in detail in Chapter 2; however, brief consideration is merited here as it gives relevance to the discussion on equalization.

3.2 Evaluation of Flow Equalization Experience

If the premise is accepted that flow equalization should lead to both improved process performance and simplified operation as indicated by theoretical considerations, then there is most likely one (or more) of three possible reasons why contrary opinions have been voiced; either

- (1) The process parameters used to evaluate performance under equalized and unequalized flow periods were not appropriately selected; and/or
- (2) The tests were conducted on plants where the biological process operating parameters (i.e. sludge age, etc) tended to mask the expected beneficial effects of flow equalization; or

- (3) Difficulties were encountered in operation of the equalization facility, resulting, in fact, in a poor degree of flow equalization.

3.2.1 Process Parameters for Performance Evaluation

Comparison of process performance under equalized and unequalized flow conditions has been based almost exclusively on the respective (1) effluent COD (or BOD) concentration, and (2) effluent TSS concentration, for the different flow conditions. With regard to COD, it is widely accepted that the effluent concentration is virtually insensitive to dynamic loading conditions; the major portion of the influent COD consists of particulate material which is either adsorbed onto the sludge mass prior to synthesis or enmeshed in the sludge mass prior to adsorption - in either case the major portion of the influent COD is excluded from the liquid phase and does not appear in the effluent. In the case of effluent TSS concentration, flow equalization will show benefits in terms of effluent quality only if, under cyclic flow conditions, the secondary settling tank is *overloaded* for at least a portion of the day. If this is not so, then the evaluation based on effluent TSS concentration will show little, or no, improvement with equalization.

3.2.2 Operating Parameters During Evaluation

Most of the full-scale research and evaluation of equalization has been conducted in the USA. In that country the main concern in sewage treatment, hitherto, has been removal of COD; for this purpose operating the activated sludge plants at short sludge ages is adequate. However, at short sludge ages, the response of the process under variable input conditions is damped considerably (see Section 2.1); in such cases the efficacy of flow equalization will not be demonstrated.

3.2.3 Operating Procedures

Operational procedures for flow equalization tanks have generally been of the most elementary kind, and have been proposed on the basis of the approach used in design. The design usually has been based on the assumption of a fixed daily inflow pattern, with the size of

the tank being obtained from a cumulative mass flow hydrograph (Rippl diagram). The operational procedures for controlling the flow equalization tank normally reduced to setting the outflow rate from the tank once a day after an estimate of the mean inflow rate for the ensuing 24 hour period has been made. It would appear that herein lies the essence of the problem encountered in flow equalization - plant operators find difficulty in making the correct decision in estimating the required tank outflow rate i.e. the quality of flow equalization achieved depends totally on operator ingenuity and experience.

3.3 Motivation for Application of Equalization in South Africa

From the discussion of Sections 3.2.1 and 3.2.2 it is evident that many of the criticisms levelled against flow equalization have little bearing on whether or not this approach can supply an effective mechanism for the control of wastewater treatment plants in South Africa. In fact, as regards the South African application (long sludge ages, nutrient removal processes, etc), much of the past research into equalization should be re-assessed before making a pronouncement on the benefits that possibly can be derived. However, even if the theoretical indications are that equalization (of both flow and load) will provide an effective alternative to in-plant control, two problems must still be surmounted if a practical equalization procedure is to be developed:

- (1) Even if equalization of flow is effective, equalization of load may not be significant with the result that extensive in-plant control is still required to counter the effects of load rate variations. Therefore, it is necessary to investigate possible means for simultaneous optimal attenuation of both flow and load rates (noting that these parameters are interrelated).
- (2) Even with flow equalization alone, if operation is to be successful then it is necessary to develop an effective control procedure which will overcome the difficulties inherent in present operational methods.

4. PROPOSED EQUALIZATION METHOD

The principal problem in the current approach to flow equalization has been identified as the lack of an effective operational procedure which ensures efficient equalization. It is not surprising that operators experience difficulties in making estimates of the required equalization tank outflow rate settings; although the inflow rate patterns may be similar from day to day, they are not identical, particularly in the transition from a week to a weekend, and *vice versa*. In view of the problems encountered with the level of operator competence in South Africa, it is unlikely that even flow equalization can be applied effectively in this situation. It is even less likely, therefore, that any operational procedure designed to provide simultaneous flow and load equalization could ever be applied successfully if there is to be a heavy reliance on operator expertise.

A second problem inherent in the current design approach is that no solution is provided in the event of the tank becoming too small to ensure complete flow equalization. The tank is sized on the basis of a selected inflow pattern (together with a factor of safety for unusual flows, perhaps). However, if for some reason there is an increase in the mean daily inflow to a plant, the situation may arise where it is no longer possible to withdraw a constant outflow rate from the tank. In this case the present design method with its implicit operating procedure will break down.

The current problem encountered in the control and operation of an equalization facility operated by manual agency is very similar to the one previously encountered with in-plant control. In in-plant control there has been a move away from operator-dependent control strategies towards fully automated systems. Therefore, it is probable that this direction should be followed also with equalization.

The approach of developing an equalization control strategy which can be used to operate an equalization facility on a continuous basis is, in fact, the reverse of the usual approach to design. Current practice is to size the flow equalization basin such that, under a fixed 24 hour input pattern of flow rate, sewage can be withdrawn from the tank at a constant rate. The implicit assumption for

successful operation with this method is that the daily inflow is repeated very closely from day to day; because this behaviour generally is not exhibited, the method breaks down. However, by taking the control strategy approach, the fact that the daily input pattern is not fixed, and varies from day to day, is of little consequence - once a suitable strategy has been developed it can be linked up to control an equalization tank of any size i.e. the implicit assumption here is that the strategy accepts that the effective size of the tank (in terms of the mean retention time based on the average daily input) varies from day to day. This means that, even if a particular tank is not sufficiently large to allow complete equalization, the control strategy will still ensure optimal utilization of the available capacity.

The purpose of this investigation is to develop such a strategy for the automatic control of equalization basins which will overcome problems inherent in manually-controlled operating procedures. The approach that will be used here is to develop an on-line microprocessor-based "intelligent" control strategy where the optimal outflow rate from the tank is specified from the microprocessor on the basis of application of some optimization procedure.* The advantage of this approach is that the computational capacity of the microprocessor allows application of an optimization procedure which can be used to determine the tank outflow rate that will result in optimal simultaneous equalization of flow and load rates. Such a scheme, if successful, should provide an effective alternative to in-plant

* Using a microprocessor-based equalization control strategy as an alternative to complex in-plant control may appear to be a contradiction in terms, considering that a microcomputer system is, itself, a complex piece of electronic equipment. However, the large amount of research directed towards the development of microcomputers has resulted in relatively low-cost items which provide extremely reliable operation. Servicing of microcomputer equipment has also been simplified through the modular approach in design - replacing unserviceable components usually only involves exchanging slot-in cards. Consequently, the back-up service required is of a relatively simple nature. These features have resulted in wide application of microprocessors in industrial control applications and provide a natural path for the development of control systems in the wastewater treatment field. The microprocessor, therefore, is not likely to constitute a problem in the implementation of the strategy.

control, particularly in the South African context, and is worthy of intensive study.

CHAPTER TWO

LITERATURE SURVEY

1. NATURE OF INFLUENT FLOW AND LOAD VARIATIONS

It is generally recognized that wastewater flows exhibit daily cyclic patterns of volumetric flow rate and concentration, and consequently, in load rate. In the design of wastewater treatment plants it is common practice to describe the cyclicity of flow and load by two parameters: the mean daily average values and the mean daily peak values. In the case of flow, the mean daily average during dry periods is called the Dry Weather Flow (DWF) and the mean daily peak the Peak Dry Weather Flow (PDWF); during rainy weather the corresponding flows are the Wet Weather Flow (WWF) and the Peak Wet Weather Flow (PWWF).

The DWF is the sum of two components - the sanitary contribution and the contribution from ground water infiltration. Infiltration depends on factors such as the rainfall, the water table, type of sewer joint used, the length of sewer, and the age of the sewer. The WWF is the sum of three components - the sanitary contribution, the ground water infiltration contribution, and the ingress of storm water. Traditionally the relation between the peak and the average flows has been quantified in terms of the size of the population being served (see Fig 2.1, after Ongerth, 1979). Similar empirical relationships have been developed for relating the peak and average loads. The relation between peak and average rate of flow and load from industrial districts varies so greatly with the type of industry that it is difficult to formulate reliable empirical relationships.

The empirical relationships discussed above do not supply any information regarding the *form* of the daily cyclic influent flow and load patterns entering a wastewater treatment plant; the relationships only provide information concerning the ratio of peak to mean values. In order to evaluate the effectiveness of equalization as a possible component in the design of a treatment plant the form of the cyclic variation in flow and load over the day is needed.

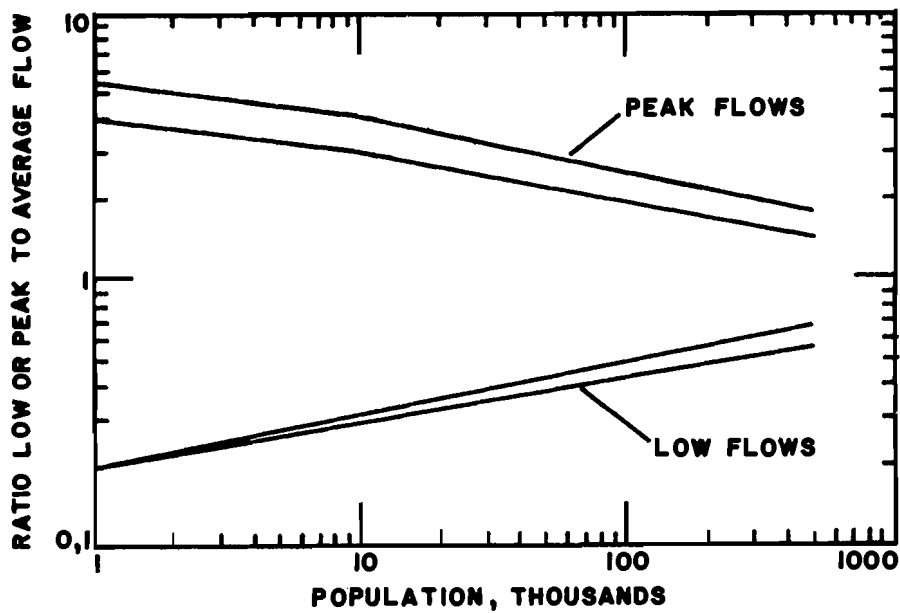


Fig 2.1 Dependence of extreme flow ratios in municipal sewers on population (after Ongerth, 1979).

A typical diurnal flow and load pattern taken from an Environmental Protection Agency (EPA) publication (EPA Technology Transfer Seminar Publication, 1974) is shown in Fig 2.2. Both flow and concentration,

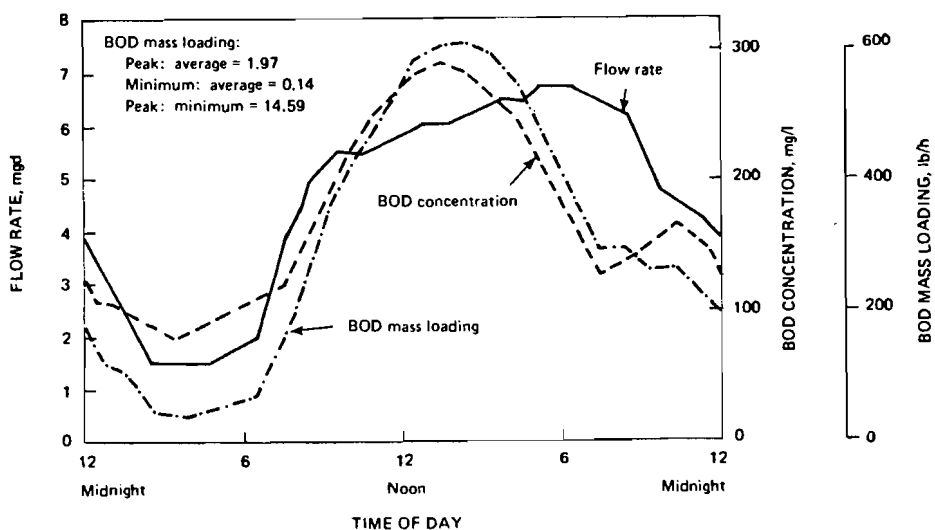


Fig 2.2 Diurnal raw wastewater flow and BOD variation in influent stream to a WWTP (after EPA, 1974).

and consequently load, drop to low values during the night, rise during the morning, and attain a maximum soon after midday. The influent flow and load patterns, given in Fig 2.2, have been substantiated by many observers as typical for a municipal wastewater treatment plant (Ekama and Marais, 1978; Boon and Burgess, 1972). In South Africa a typical example is the mean pattern for data collected over a period of one week at the Goudkoppies Sewage Works, Johannesburg (Johannesburg City Engineer's Department, 1979), shown in Fig 2.3.

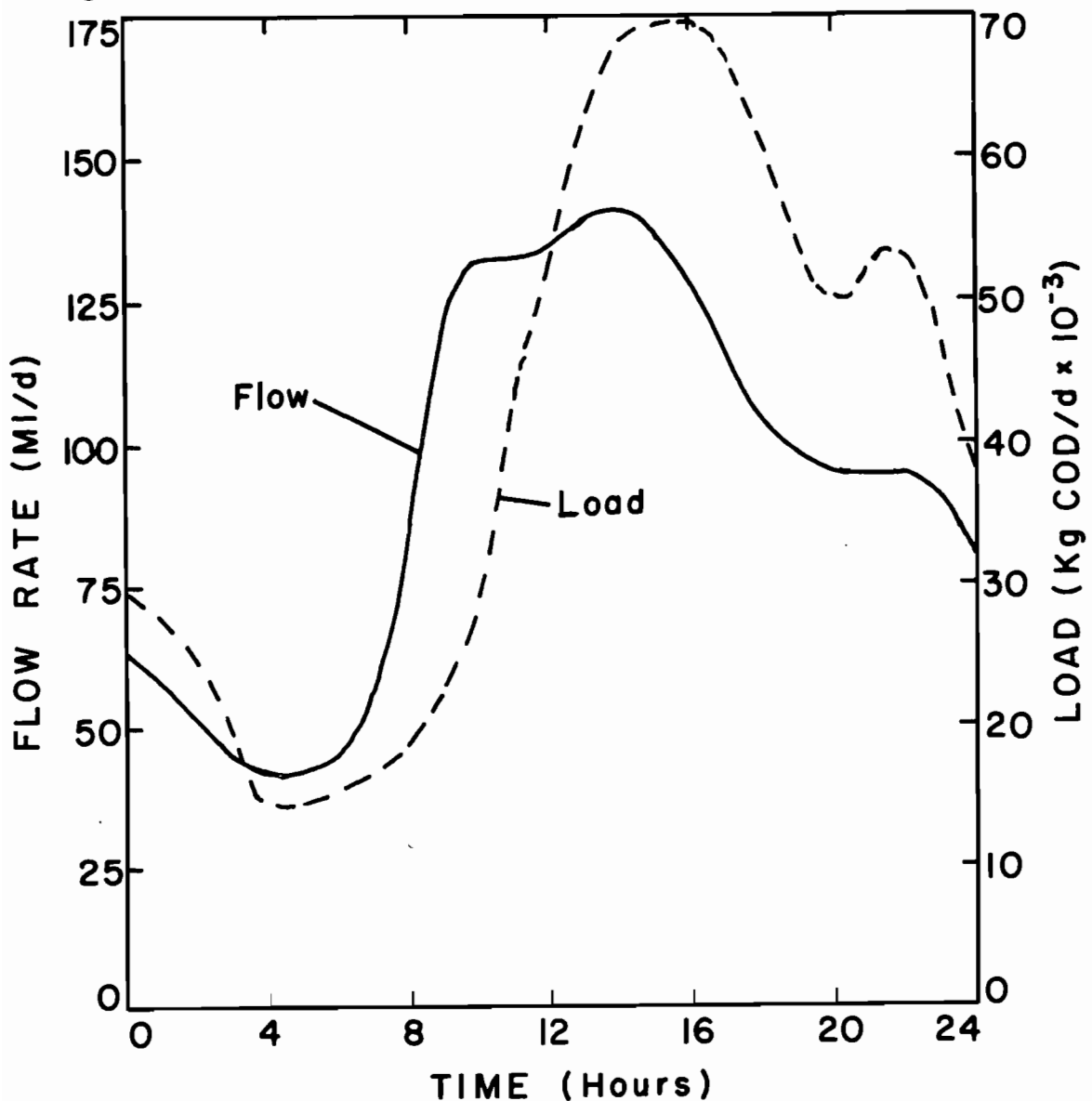


Fig 2.3 Mean diurnal cyclic flow rate and mass loading pattern for data collected over a period of one week at the Goudkoppies Sewage Works, Johannesburg.

Very little information is available for estimating the form of the daily cyclic patterns of flow and load. Qualitatively the patterns of flow and load depend on a combination of the following factors:

(i) Type of sewer system:

Sewer systems can generally be categorized into two types; (a) separate systems, in which the sewers are designed specifically to carry sanitary flow; storm water is excluded, as far as possible, from entry into the sewer; and (b) combined systems in which provision is made for transporting of both the sanitary and storm flow. Almost without exception sewer systems in South Africa are of type (a) - efforts are continually being made to eliminate connections which allow storm water to enter the sanitary sewers.*

(ii) Layout of sewer system:

The effect of the layout of the sewer system can be appreciated from consideration of Figs 2.4(a) and (b). If points A, B and C are sources of wastewater with similar inflow patterns to the main interceptor sewer it is evident that the discharge pattern will differ between the two layouts. Furthermore, sewer lengths and gradients will determine the time of transit in the sewer and whether settlement, with periods of flushing, will occur.

(iii) Climatic/seasonal effects:

The daily influent patterns are affected on a seasonal basis; the extent of these changes will largely be determined by the amount and frequency of rainfall, and by the topography and soil conditions. For example, in Cape Town, which falls in a winter rainfall region, experience has shown that in winter there is an increase in the average daily flow rate, with a concomitant decrease in the average *concentration* (but not necessarily the load). These changes are principally due to

* Equalization of wet weather flows from combined storm and sanitary sewers usually will require very large equalization basins. The principles developed in this report for equalization of flows are the same for separate and combined wastewater flows but attention will be focussed only on flows from sanitary sewers in separate systems.

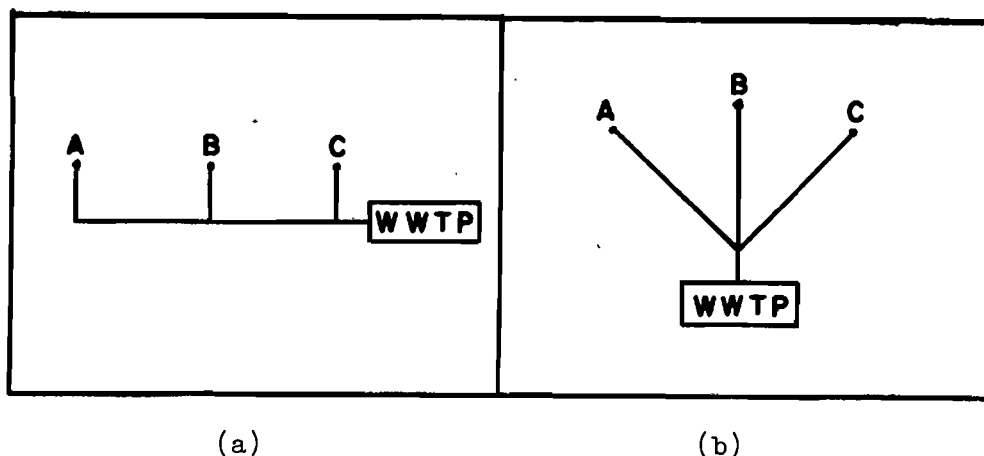


Fig 2.4 Effect of sewer layout on flow and load pattern experienced at WWT plant.

an increase in both ground water infiltration and ingress of storm water.

(iv) Population structure:

In general WWT plant's receive inflow from industrial as well as domestic sources. The nature and contribution of these sources will, in turn, depend on the nature of the industry and the social structure of the population being served. Whereas the effluent flow from a particular industry tends to be unique to that industry, the social structure has a consistent effect: as the social class of the contributors increases so the flow increases concomitantly. This response, however, is relative; the absolute magnitude of the flows per person in each class will depend on the cost of the water, whether the supply is metered and the general social attitude to water conservation.

(v) Week-weekend effects:

Waste flow patterns tend to vary between week and weekend days. When either industrial or commercial districts form an appreciable portion of the waste collection area the flow and load are likely to differ from weekdays to the weekend both in terms of the mean daily values and the form of the influent patterns. This is illustrated in the flow and load patterns measured over one week at the Goudkoppies Sewage Works, Fig 2.5.

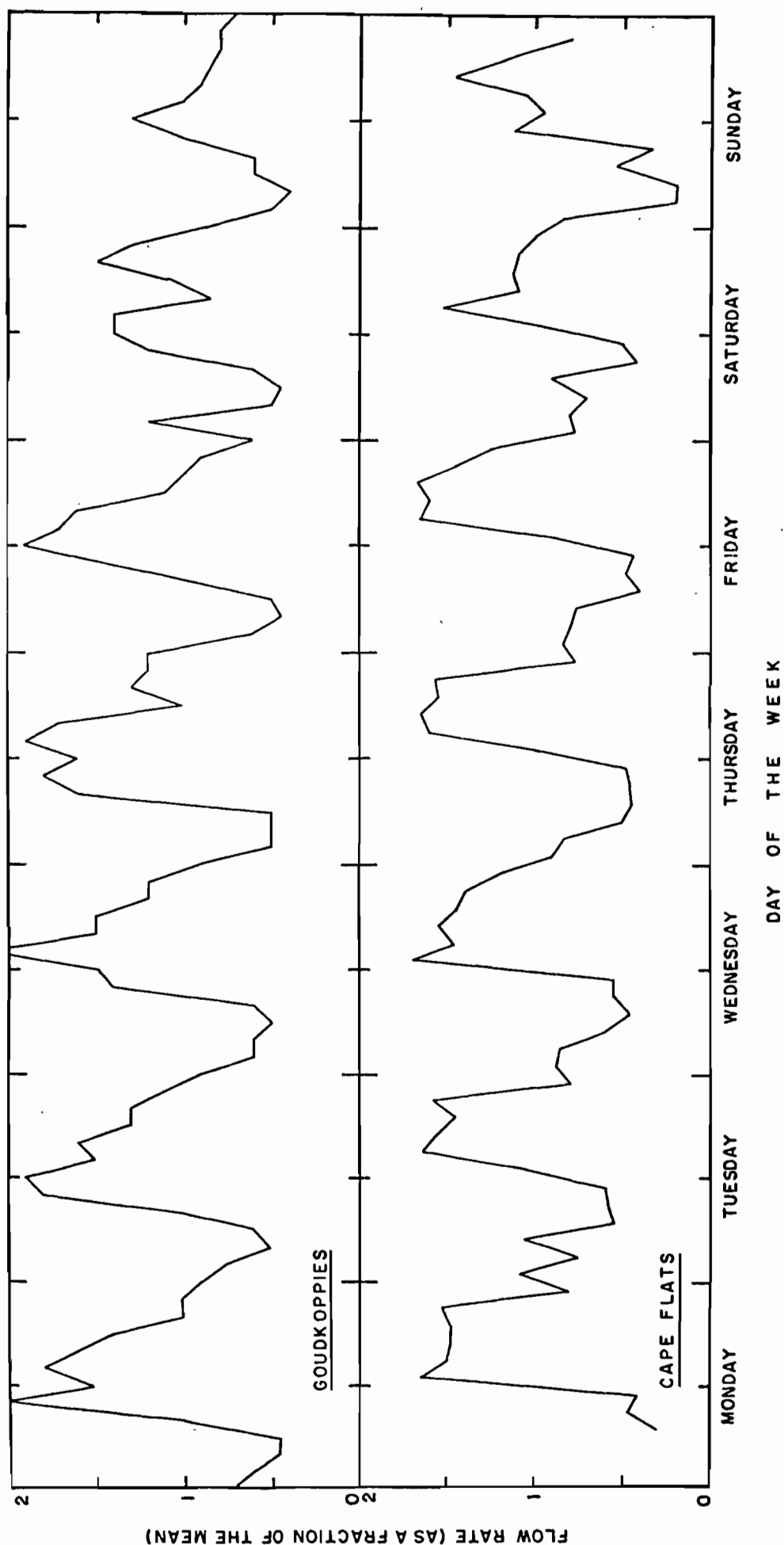


Fig. 2.6 Comparison of the raw wastewater flow variations in the influent streams to the Goudkoppies WWTW, Johannesburg, and the Cape Flats WWTW, Cape Town, over a period of one week (Flow rate expressed as a ratio with respect to the mean weekly values).

source areas. Then with an appropriate combination of these, in a specified sewer layout, a general method for predicting the expected flow and load pattern at the discharge point of the main sewer may become possible.

2. OBJECTIVES OF EQUALIZATION

Traditionally, the primary objective of equalization basins for wastewater treatment plants has been to reduce the diurnal variation in the inflow pattern, i.e. *flow* equalization. For example, Ongerth (1979), in a comprehensive evaluation of equalization in wastewater treatment, defines equalization as "any facilities and procedures for minimizing variations in the flow through treatment plants". The optimal situation is regarded as that where the downstream process receives a constant flow (EPA, 1974; Foess, Meenahan and Blough, 1977). Attenuation of variations in pollutant concentration and mass loading resulting from the mixing of streams of varying concentration in the equalization basin has been regarded as a desirable by-product or, as a secondary objective. Generally, in the literature, very little importance has been attached to *load* equalization *per se*.

The benefits to be derived from flow equalization have been variously set out. The U.S. EPA (1974) considers equalization of flow rate as one of the alternatives available for upgrading existing wastewater treatment plants for one or more of three major reasons:

- (1) To meet more stringent treatment requirements: equalization may help improved effluent quality to be attained through:
 - permitting process optimization and improving performance of existing treatment components
 - improving reliability by minimizing flow and load peaks
 - reducing effects of shock loading and slugs of toxic material.
- (2) To increase hydraulic and organic loading capacity: equalization may allow continued operation in treatment units that have reached capacity under peak flow conditions.
- (3) To correct or compensate for performance problems resulting from improper plant design and/or operation: equalization may over-

come design deficiencies and reduce operational problems through:

- being more economical than correcting the actual deficiencies
- providing for simplified operation, and thus minimizing the possibility for operational errors.

Specific benefits accruing from flow equalization in activated sludge treatment plant operation have been identified by a number of authors (La Grega and Keenan, 1974; Wallace, 1968; Spiegel, 1974; Ongerth, 1979):

- (a) Improved performance of primary sedimentation basins and secondary clarifiers.
- (b) Increased capacity of sedimentation and clarification units in existing plants and specification of smaller units for new plants.
- (c) Improved biological process response through a partial reduction in food/micro-organism loading peaks.
- (d) Simplified control of in-plant flow rate dependent operations such as chemical dosing and recycle pumping.
- (e) Lower energy tariff charges by reducing peak power demands for pumping and aeration.
- (f) Lower capital costs by not having to supply the oxygenation capacity to match the peak load requirement.
- (g) Reduction in shock loading effects by discharging recycled concentrated waste streams such as digester supernatant and sludge dewatering filtrate to the equalization basin.

Before evaluating the extent to which these benefits have been realized in existing equalization facilities it is necessary to consider (1) the types of equalization configuration used, and (2) design methods for equalization facilities; these two features have a bearing on the discussion that follows.

3. EQUALIZATION CONFIGURATIONS AND MODES OF OPERATION

Equalization basins have been included in plant designs in various

configurations, and using different modes of operation.

The basic configurations and modes of operation which may be applied to equalization basins are shown in Fig 2.7. The basin may be operated in the *constant volume mode* or the *variable volume mode*.

3.1 Constant Volume Mode

In this mode a fixed hold-up volume is provided for the influent flow, and concentration fluctuations are attenuated, as may be shown by dynamic studies (Novotny and Englands, 1974). Since the tank is continuously full, however, the rate of outflow always equals the inflow, and flow fluctuations are not reduced. The constant volume mode of operation thus produces some damping of mass loading variations but does not alleviate the problems due to uneven flow.

3.2 Variable Volume Mode

In the variable volume mode of operation the outflow rate from the tank is regulated, allowing the tank hold-up to vary. Consequently the tank capacity is used for both flow and mass loading equalization; it is readily shown (Andrews, Buhr and Stenstrom, 1977) that by reducing variations in flow rate, a substantial reduction in load fluctuations may be obtained.

Two types of physical configuration have been employed for a variable volume equalization process (EPA, 1974; Foess, Meenahan and Blough, 1977), see Fig 2.8. These are:

- (a) A "side-line" arrangement, where only a portion of the influent flow passes via the equalization tank, while the balance flows directly to the downstream process, or
- (b) An "in-line" arrangement, where all the influent flow to the process passes through the equalization basin.

Types of layout envisaged for a WWTP using these configurations are shown in Fig 2.8. It may be noted that the "in-line" configuration is simply a subset of the "side-line" configuration in that the whole flow, instead of a portion, is diverted to the equalization tank and no flow passes directly to the downstream process.

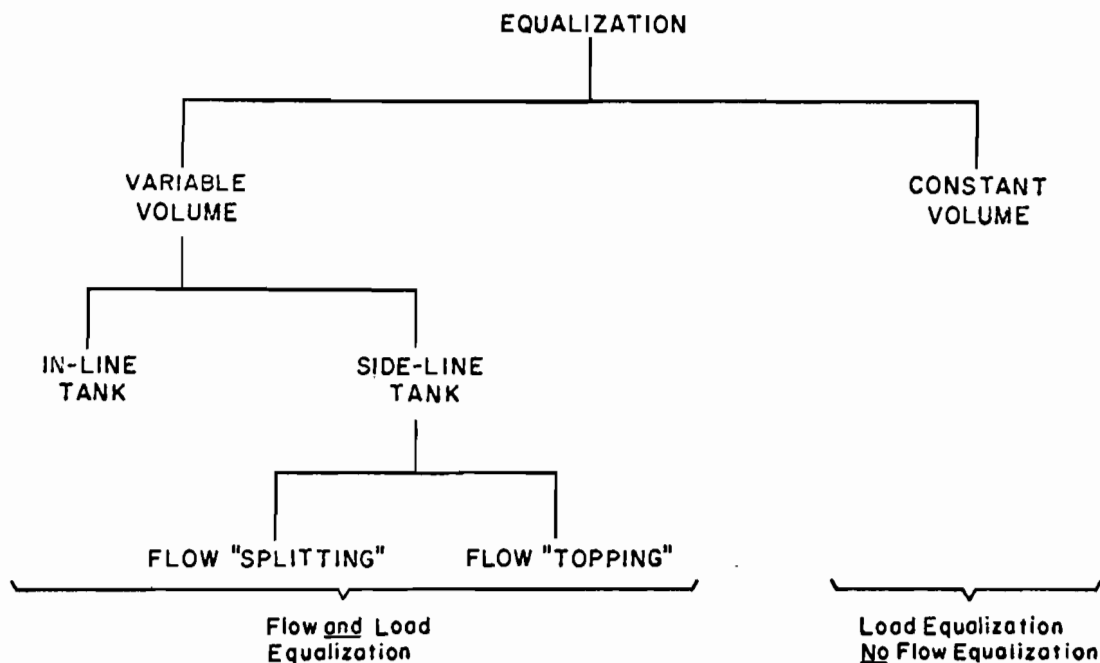
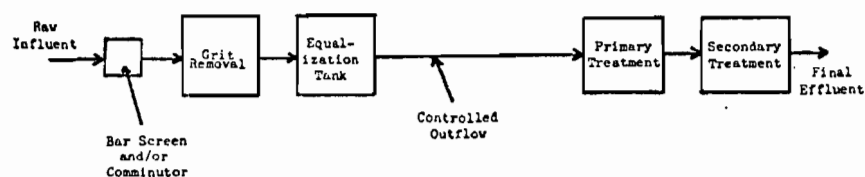
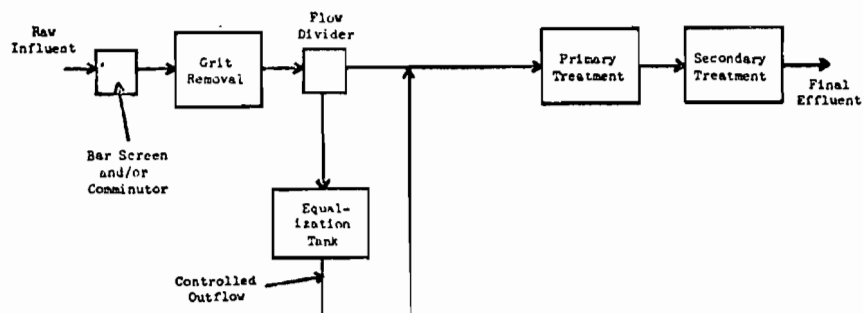


Fig 2.7 Hierarchy of Equalization.



(a)



(b)

Fig 2.8 Schematic flow diagrams of equalization facilities:
(a) in-line equalization; (b) side-line equalization.

Flow division in "side-line" equalization

There are a number of ways in which the division of flows to a "side-line" equalization tank may be achieved. Among these, the most important are:

- (i) Flow "splitting", where the influent flow is continuously divided by means of a splitter box, with a fixed fraction of the temporal flow passing via the equalization tank, the remainder passing directly to the downstream process;
- (ii) Flow "topping" (or "peak topping"), where flows above a certain amount are diverted to the equalization basin, the remainder passing directly to the downstream process.
Topping may be achieved by means of an overflow weir from a wet well equipped with a V-notch weir.

4. DESIGN METHODS FOR EQUALIZATION

In an EPA publication (1974) the design of an equalization basin is stated to require the selection and/or evaluation of the following factors:

- (i) In-line versus side-line basins
- (ii) Basin volume
- (iii) Type of construction - earthen, concrete or steel
- (iv) Mixing equipment
- (v) Pumping and control method
- (vi) Location of equalization basin within treatment system.

In the literature consideration has generally been limited to the determination of volume requirements; the other factors listed above have been largely disregarded.

With regard to computing equalization volume requirements, traditionally there have been two approaches: (1) for *constant volume equalization* and (2) for *variable volume equalization*.

4.1 Volume Requirement for Constant Volume Equalization

The objective of constant volume equalization is to reduce fluctuations in the mass loading pattern of a particular wastewater constituent - typically the COD - by providing volumetric hold-up in

the inflow circuit to the WWTP. The equalization tank volume is held constant, and consequently fluctuations in the influent flow pattern are not reduced.

The design procedure for sizing the equalization tank is based on the mass loading pattern of the wastewater constituent being considered, and requires computing the volume necessary to attenuate mass loading variations to within a certain pre-determined range (Bradley and Oldshue, 1972). Quantitative procedures towards this end are given in the analysis presented by Di Toro (1975), similar to that of Wallace (1968). These authors relate the equalization "performance" to the ratio of effluent variation: influent variation of the mass loading rate. A criterion for design is then set. The criterion is based on the probability of the effluent load exceeding a specified value, under inputs derived from a statistical characterization of the influent flow and load rates.

Two features detract from the suitability of utilizing constant volume equalization as a means for improving WWTP performance:

- (i) No attenuation of fluctuations in the influent diurnal flow rate pattern is provided by constant volume equalization. Thus, the problems associated with having a variable flow rate through the plant still exist (e.g. settling tank control, etc.)
- (ii) The function of a constant volume tank is to reduce concentration fluctuations. Theoretically, in the limit, as tank volume is increased to infinity, there will be complete attenuation of effluent *concentration* fluctuations. However, even if concentration fluctuations are completely attenuated, the load pattern on the plant will, at best, still fluctuate in accordance with the influent flow pattern. (This feature is recognized by Di Toro, 1975). Consequently, for any volume there is a lower limit to the damping of the load fluctuations achievable with constant volume equalization.

4.2 Volume Requirement for Variable Volume Equalization

Traditionally, the objective of variable volume equalization has been

to reduce fluctuations in the influent *flow* pattern. The concomitant reduction in load fluctuations has been regarded as a desirable secondary benefit. Basically flow equalization is achieved by storing influent flows in excess of the mean daily flow, and discharging the stored volume during the periods when the inflow rate falls below the mean.

Design methods for the determination of the basin volume for *flow* equalization have used, most often, variations of Rippl's mass flow technique (EPA, 1974; Speece and La Grega, 1976; Click and Mixon, 1974). The procedure requires the selection of a diurnal influent flow pattern; using this pattern in the Rippl mass flow diagram, the volume of the basin required for complete flow equalization is determined. Application of the method is illustrated below, following the procedure as set out by the EPA (1974):

The diurnal flow pattern selected consists of averages of the hourly influent flow rates measured at the Goudkoppies Sewage Works, Johannesburg, over the period Monday 5th - Friday 9th, August 1979 (see Fig 2.5). Corresponding average influent COD concentration data for the period is listed with the inflow data in Appendix A. Fig 2.9 shows the selected diurnal influent flow and load patterns.

From the diurnal flow pattern, a hydrograph is constructed by plotting the cumulative volume of influent flow (taking, say, hourly increments) as ordinate versus time of day as abscissa. The resulting hydrograph is shown in Fig 2.10.

Information regarding the equalized flow rate and the volume required for flow equalization is taken directly from the hydrograph:

- (i) The constant flow from the equalization tank is obtained from the total cumulative volume QR , over the day, and is given by slope, SQ , i.e. line A in Fig 2.10. In this case the equalized flow rate is 100,6 Ml/d.
- (ii) To achieve flow equalization enough tank volume must be provided to accumulate flows in excess of the equalized flow rate. To determine this volume the mass flow hydrograph is enveloped by two lines (B and C in Fig 2.10) parallel to the average flow

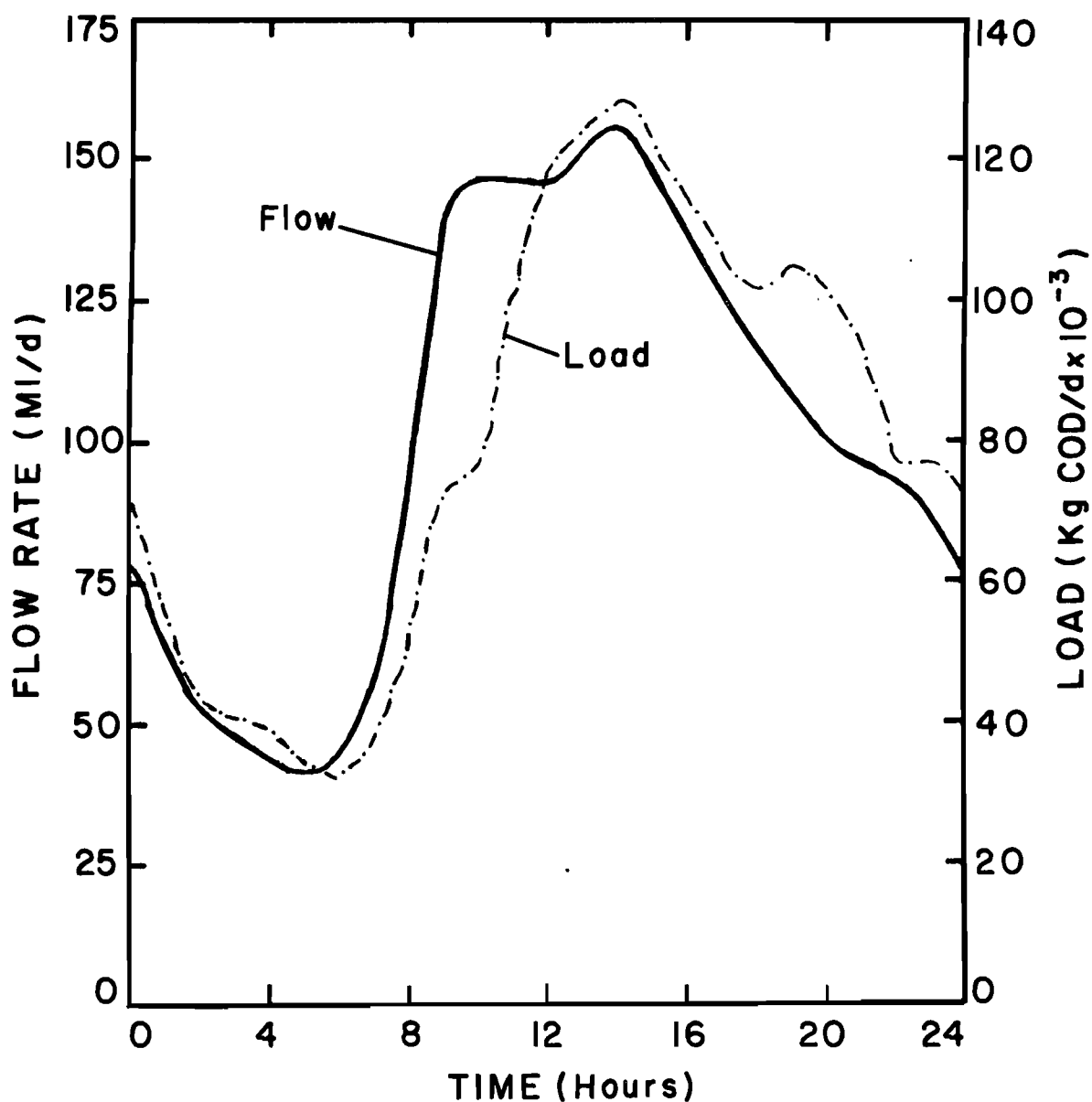


Fig 2.9 Average influent flow and COD load pattern for the Goudkoppies Sewage Works for the period 5/8/79 to 9/8/79.

line (A), and tangential to the extremities of the cumulative volume curve. The required equalization volume is given by the vertical difference between lines B and C. In this case, the required volume is 17,6 Ml, which corresponds to a tank retention time of 4,2 hours, based on the average influent flow rate.

If, in Fig 2.9, a horizontal line is drawn representing the equalized

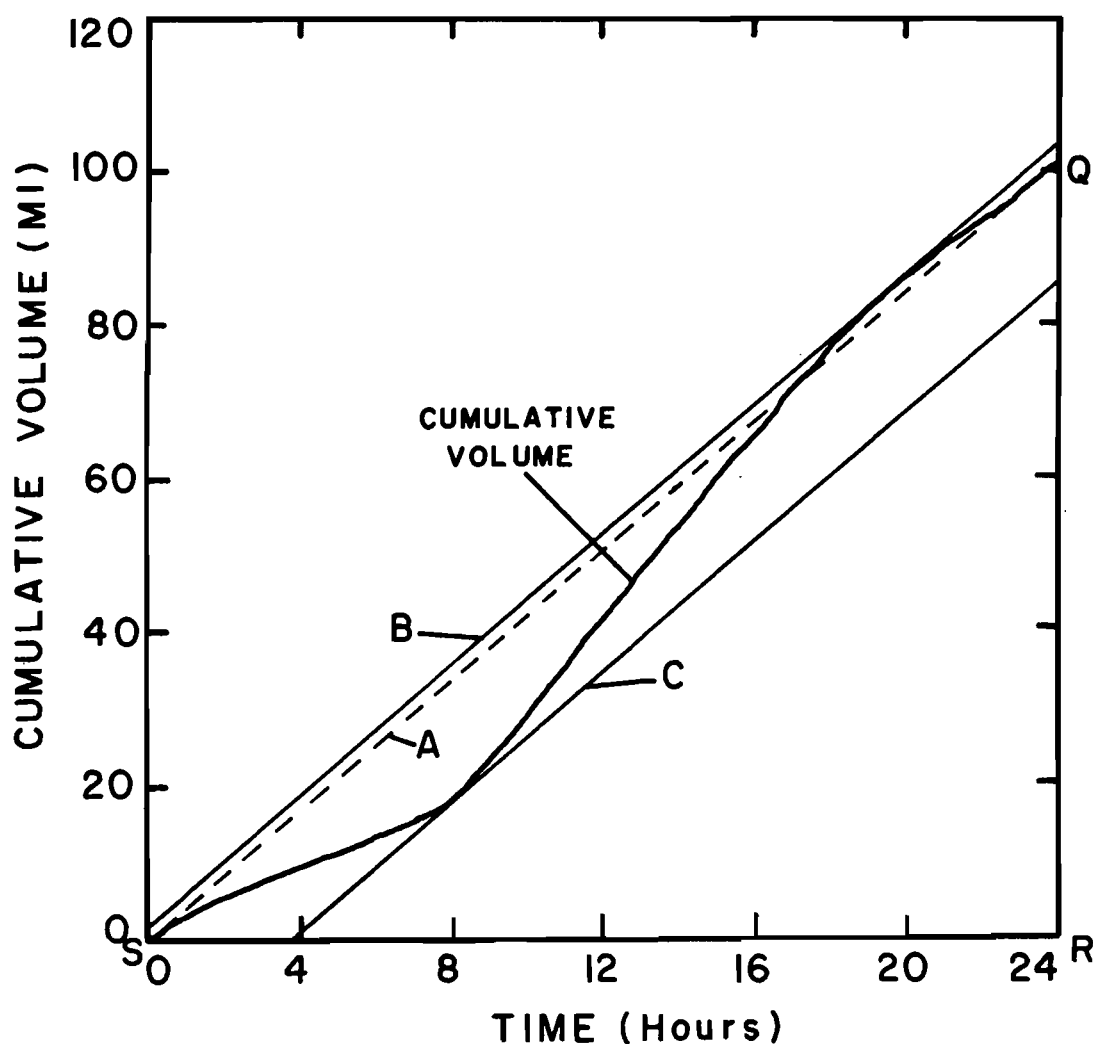


Fig 2.10 Mass flow hydrograph for the diurnal influent flow pattern of Fig 2.9.

tank outflow rate, at a value of 100,6 Ml/d, it is evident that the inflow rate equals the outflow rate at 08h00 and 20h00. Within this period the inflow rate exceeds the outflow, and the tank is filling. After 20h00, and until 08h00 in the following cycle, the tank outflow exceeds the inflow, and the tank is emptying. Interpretation of the hydrograph is facilitated if one commences at some point, taking the tank volume at that time. Balancing inflow and outflow, it is evident that at 08h00 the hypothetical tank is empty, and the inflow equals the outflow, as signified by the slope of the tangent to the mass flow curve being equal to the slope of line A. After 08h00, until 20h00, the slope of the tangent is greater than the slope of

line A (giving the equalized flow rate), and the tank hold-up increases. At 20h00 where the slope of the tangent to the mass flow curve is again equal to the slope of line A, the tank volume reaches a maximum, and begins to decrease. The hold-up of the tank at any time is given by the vertical distance between the cumulative volume curve and line C. Fig 2.11 shows how the tank hold-up would vary over the day in order to enable the constant outflow to be withdrawn.

The effluent COD concentration from the equalization tank is readily determined from the influent flow rate and COD concentration once the hold-up variation over the day is known. This determination involves material balance principles, assuming completely mixed conditions, starting at the time when the tank is empty for, at that point, the effluent concentration must equal that of the influent; details of the calculation procedure are given in Chapter 3 where the dynamic response of the concentration is presented.

The effect of equalization of the influent flow pattern in Fig 2.9 is illustrated in Fig 2.12 where the diurnal effluent COD mass loading pattern after equalization is shown. The peak to average COD mass loading rate is reduced from 1,62 to 1,15 (a reduction of 29%) and the peak to minimum is reduced from 3,86 to 1,71 (a reduction of 56%).

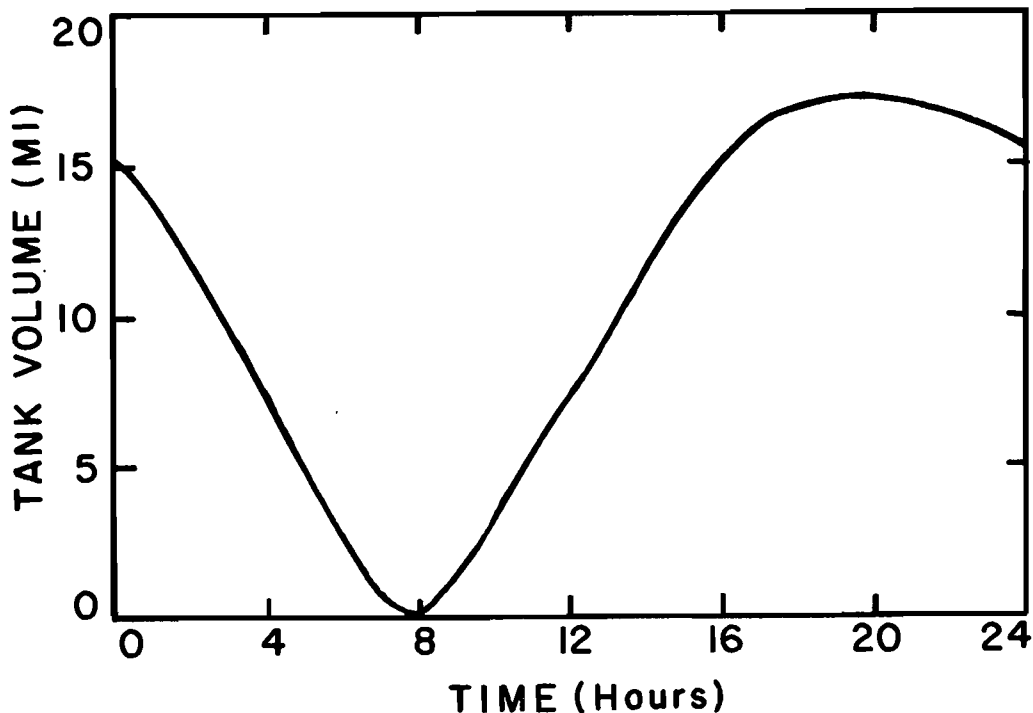


Fig 2.11 Tank volume variation.

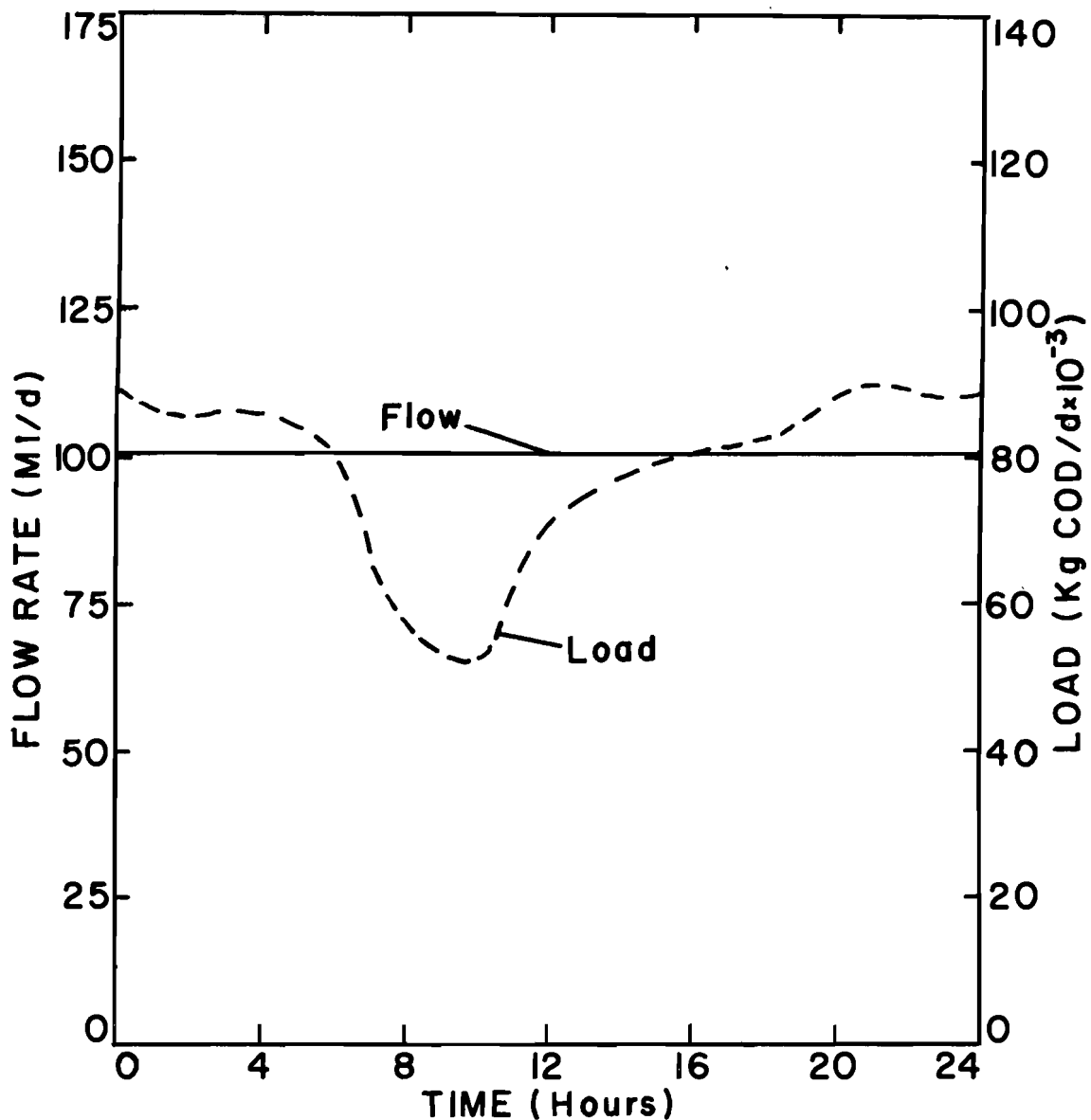


Fig 2.12 Effluent diurnal flow and COD mass loading patterns (cf. Fig 2.9)

From Figs 2.11 and 2.12 it is evident that the deviation in tank COD concentration (or load) is most pronounced (i.e. least damped) when the equalization tank volume is close to its lowest level. This effect can be reduced by increasing the tank volume above the theoretical minimum required for flow equalization, thereby providing for more effective dilution of the influent flow fluctuations. The EPA (1974) suggests an increase in the volume of the equalization tank above the minimum required, for the following reasons:

- (i) When the tank volume is a minimum there must be a certain minimum depth remaining to accommodate stirrers (or floating aerators) for mixing.
- (ii) Sufficient volume should be available at all times to provide dilution of slugs of toxic or highly concentrated waste in the influent.
- (iii) An upper reserve volume must be provided to accommodate unforeseen peaks in diurnal influent flow.

In the example presented by the EPA (1974) a 33 percent increase above the minimum tank volume is suggested as adequate.

As an alternative to the graphical method, a simple tabular method for determining the volumetric requirement may be used (Ongerth, 1979). The differential equation describing the tank volume response is

$$dV/dt = F_o - F_l \quad (2.1)$$

where

V = tank volume

F_o = influent flow rate

F_l = effluent flow rate

t = time

Equation (2.1) can be written in its discrete form as

$$\bar{F}_o \Delta t = V + \bar{F}_l \Delta t \quad (2.2)$$

where

\bar{F}_o, \bar{F}_l = average influent and effluent flow rates, respectively, over the interval Δt .

The mass flow balance relationship, Eq (2.2), is applied step by step in the tabular method; the computations are summarized in Table 2.1:

A uniform time increment, Δt , of 1 hour is taken as a suitable value compatible with normal diurnal variations. The basin is assumed to be at a reference level of 0 at midnight. From a repetitive application of Eq (2.2) the cumulative volume change, $\Sigma \Delta V$, is obtained; the required

Table 2.1 Results of Tabular Method of Volume Determination

Time interval, 1 hr from	\bar{Q}_{in} Mℓd ⁻¹	$\bar{Q}_{in} \Delta t$ Mℓ	$\bar{Q}_{out} \Delta t$ Mℓ	ΔV Mℓ	$\Sigma \Delta V$ Mℓ
00h00	72,3	3,01	4,20	-1,18	- 1,18
01h00	59,4	2,48	4,20	-1,72	- 2,90
02h00	50,4	2,10	4,20	-2,10	- 5,00
03h00	45,6	1,90	4,20	-2,30	- 7,30
04h00	42,4	1,77	4,20	-2,43	- 9,73
05h00	42,8	1,78	4,20	-2,41	-12,14
06h00	50,8	2,12	4,20	-2,08	-14,22
07h00	73,3	3,05	4,20	-1,14	-15,36*
08h00	112,0	4,67	4,20	0,47	-14,89
09h00	141,0	5,88	4,20	1,68	-13,21
10h00	146,4	6,10	4,20	1,90	-11,30
11h00	145,5	6,06	4,20	1,87	- 9,44
12h00	148,3	6,18	4,20	1,98	- 7,45
13h00	153,5	6,40	4,20	2,20	- 5,25
14h00	152,1	6,34	4,20	2,14	- 3,11
15h00	143,4	5,98	4,20	1,78	- 1,33
16h00	132,1	5,50	4,20	1,31	- 0,03
17h00	121,8	5,08	4,20	0,88	0,85
18h00	112,9	4,70	4,20	0,51	1,36
19h00	104,3	4,35	4,20	0,15	1,51*
20h00	98,2	4,09	4,20	-0,10	1,41
21h00	94,7	3,95	4,20	-0,25	1,16
22h00	90,4	3,77	4,20	-0,43	0,73
23h00	83,1	3,46	4,20	-0,73	0,00

$Q_{out} = 100,7 \text{ Mℓ.d}^{-1}$

$\Delta t = 1 \text{ h} = 0,0417 \text{ d}$

$\Sigma \Delta V = \text{running total of } \Delta V \text{ values}$

Working volume required = $1,51 - (-15,36) = 16,87 \text{ Mℓ}$

tank hold-up is given by the difference between the maximum value and the minimum value of $\Sigma \Delta V$. In this case a volumetric hold-up of 16,9 Ml is required (cf 17,6 Ml from the graphical method). Because the two methods are equivalent, i.e. both based on a simple flow balance, the required volume should be identical in each case; the small difference arises from (1) the error incurred through using a relatively long increment, Δt , and (2) the limited accuracy in plotting and reading the cumulative mass flow diagram.

Both the graphical and the tabular methods, for the determination of the volume requirement for flow equalization, involve a step by step procedure. If the diurnal influent flow rate can be represented by a simple function then there is a simple analytical solution for the problem. Two methods have been proposed using this approach; those of (1) Smith, Eilers and Hall (1973) in which the influent flow rate pattern is represented by a sine wave with a period of one day, and (2) Click and Mixon (1974), where the influent flow rate pattern is represented by a rectangular wave.

Sine Wave Method: The flow rate equation used by Smith *et al* (1973) is of the form:

$$F_o(t) = F_{av} - (F_{max} - F_{av}) \sin 2\pi t \quad (2.3)$$

where

$F_o(t)$ = influent flow rate as a function of time

F_{av} = average inflow rate

F_{max} = peak influent flow rate

t = time, d

If a constant outflow is desired, then the volumetric requirement is obtained by integrating the difference between the influent and outflow rates from $t = 0,5$ to $t = 1,0$ day, i.e.

$$\begin{aligned} V &= \int_{0,5}^{1,0} (F_o - F_{av}) dt \\ &= (F_{max} - F_{av}) / \pi \end{aligned} \quad (2.4)$$

The size of the equalization tank can be expressed in terms of the mean hydraulic retention time, R_T , based on the average influent flow rate, F_{av} , viz:

$$\begin{aligned} R_T &= V/F_{av} \\ &= (F_{max}/F_{av}-1)/\pi \end{aligned} \quad (2.5)$$

where

R_T = mean hydraulic retention time, d

Rectangular Wave Method: The method of Click and Mixon (1974) is similar to the sine wave method, except that the influent flow rate is approximated by a rectangular wave with the ratio of peak-to-average inflow rate equal to the ratio of average-to-minimum inflow rate; this approximation would seem reasonable for many diurnal influent flow patterns.

The volumetric requirement for flow equalization, V , is given by

$$V = F_{av}(x-1)^2/(x^2-1) \quad (2.6)$$

where

x = peak-to-average flow ratio = average-to-minimum flow ratio

$$= F_{max}/F_{av}$$

The corresponding tank retention time, R_T , based on the mean inflow rate, F_{av} , is

$$R_T = (F_{max}/F_{av}-1)^2/[(F_{max}/F_{av})^2-1] \quad (2.7)$$

Figure 2.13 gives a comparison of the sine wave and the rectangular wave approaches; mean tank retention time, R_T , (volume as a fraction of the daily average inflow rate) is plotted versus the peak-to-average inflow rate, F_{max}/F_{av} . For F_{max}/F_{av} less than $(\pi-1)$ the rectangular wave method gives a slightly more conservative estimate of the volume requirement; as the ratio F_{max}/F_{av} increases above $(\pi-1)$ the sine wave method becomes rapidly more conservative than the rectangular wave method. Also plotted in Fig 2.13, as a single

data point, is the R_T vs F_{\max}/F_{av} value from application of the graphical or tabular flow balance method to the influent flow pattern shown in Fig 2. 9; the value lies between the estimates from the sine wave and rectangular wave methods.

4.3 Equalization Tank Operation

The four design procedures discussed above offer simple solutions for sizing an equalization tank; however, the solutions do not supply a procedure for *operating* an equalization tank under real-time conditions - *the solutions all presuppose fore-knowledge of an influent flow pattern which remains invariant from day to day.* Such a situation is

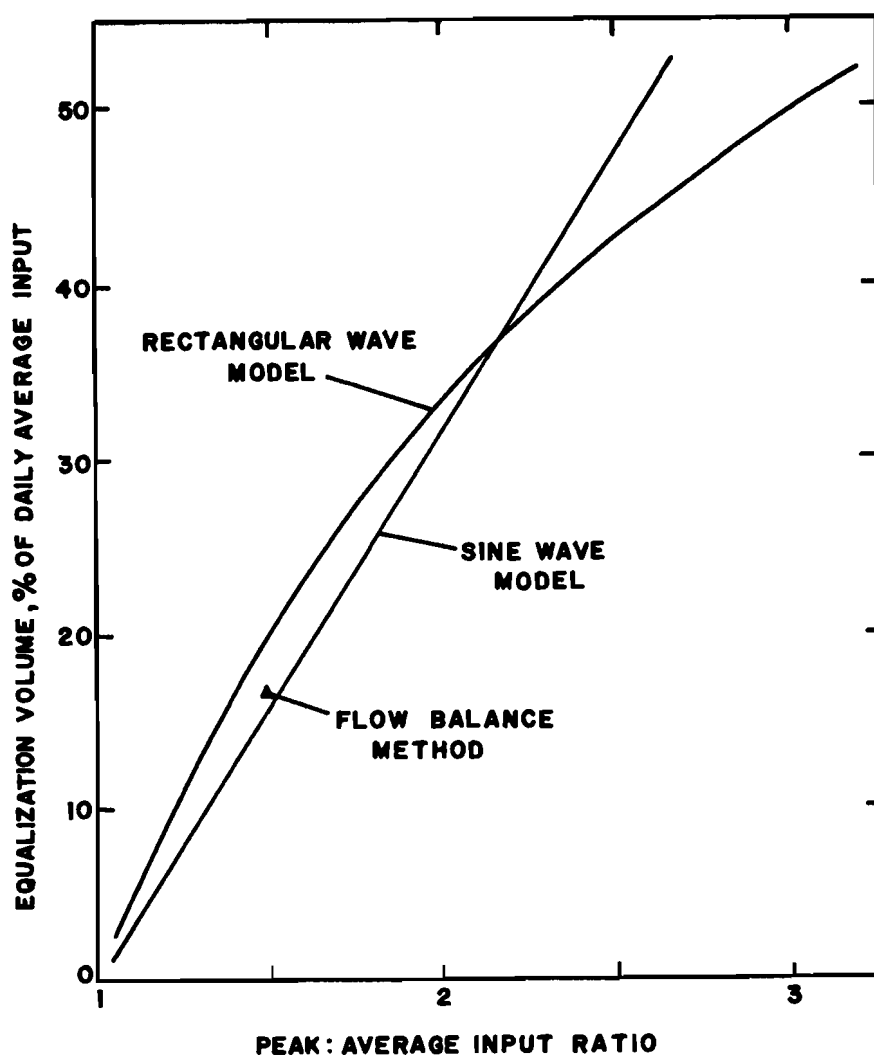


Fig 2.13 Equalization volume estimation for the different methods.

never present in practice; not only does the flow pattern vary from day to day, but also between weekday and weekend and between wet and dry seasons. To accommodate these effects operation of an equalization tank in fact requires that the outflow rate be evaluated and set several times a day to prevent tank overflow or emptying. Although it is possible to reduce the influent flow rate fluctuations, it is not possible, in fact, to obtain complete equalization. Furthermore, when these required adjustments are made by human agency, experience indicates that the operation usually is less than optimal in damping the fluctuations in flow rate. This is, for example, evident in Fig 2.14 which illustrates the equalization tank operation at the Goudkoppies Sewage Works. In this Figure, for a period of one week, both the inflow to and the outflow from the equalization tank are shown together with the tank hold-up variation over the period. It is apparent that:

- (1) Although the tank size is sufficient to allow complete flow equalization in terms of the Rippl approach, relatively inefficient damping of flow fluctuations was achieved.
- (2) About 50 percent of the tank capacity was being used for equalization; only once during the week did the tank hold-up drop below 50 percent of the maximum, while overflow occurred on 6 of the 7 days.

It is evident from the example above that provision of adequate volume for the equalization tank does not necessarily guarantee efficient equalization. For adequate flow equalization the design must provide not only an estimate of the volume requirement, but also *a strategy for the control of the real-time operation of the basin such that the flow fluctuations will be minimized.*

MacInnes, Middleton and Adamowski (1978) have recognized that a major factor contributing to a reduction in the efficiency of an equalization facility is the limitations inherent in manual operation. To overcome this problem these authors have proposed a control strategy, based on a stochastic approach, for determining the required tank outflow rate at intervals over the day. Their approach makes use of a mathematical simulation of the real-time behaviour of an "in-line"

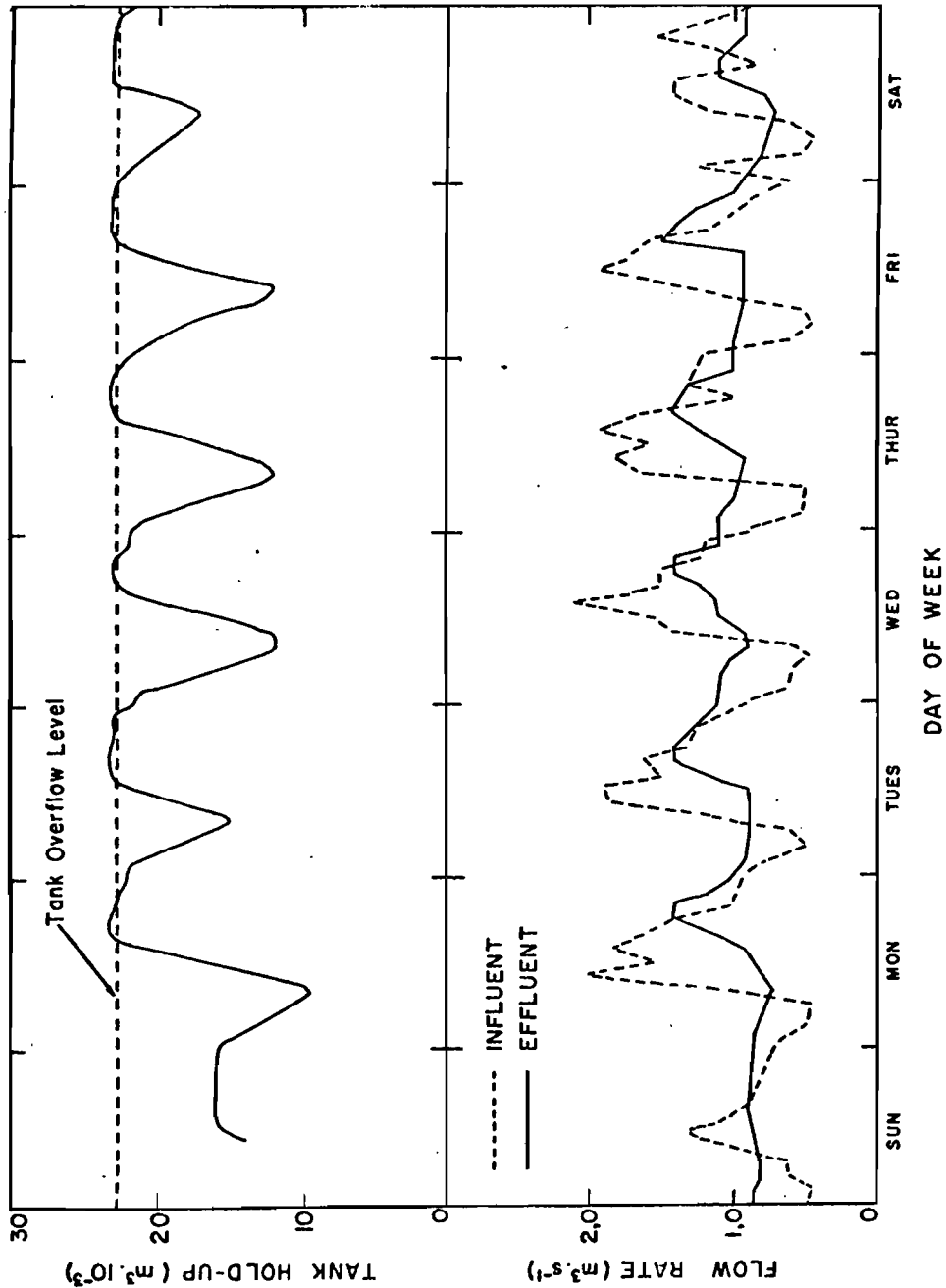


Fig 2.14 Goudkoppies Sewage Works equalization tank response over a period of one week under manual operation.

equalization process. The process is conceptualized as a dynamic system producing stochastic outflows from stochastic inflows. The influent flow rate time series, $Z(t)$, is assumed to be represented by a linearly additive model such that

$$Z(t) = Z_T(t) + Z_p(t) + Z_s(t) \quad (2.8)$$

where

$Z_T(t)$ = deterministic trend component

$Z_p(t)$ = deterministic cyclic component

$Z_s(t)$ = stochastic component.

The flow rate time series is applied at regular 3 hour intervals to forecast the *mean* flow rate for the subsequent 24 hours. This forecast then becomes the tank outflow rate for the subsequent 3 hour period. Using this approach, MacInnes *et al* (1978) encountered operational difficulties with tank underflow (emptying) and overflow. In their model the problem of tank underflow was accommodated by introducing a recycle to the upstream end of the equalization tank which was activated when tank underflow was encountered. Apparently when the maximum tank hold-up was exceeded overflow was allowed to take place.

The occurrence of underflow and overflow arises because the procedure estimates a future flow at any time based solely on a background of statistical history of the influent flow and does not take into account the hold-up status at that point. It would appear therefore that a control strategy cannot be based only on a forecast of the statistically-expected inflow rate; it should determine the required outflow rate on the basis of both (1) a forecast of the mean influent flow rate and the form of the influent pattern, and (2) the tank volume situation at the time the forecast is made. Only in this way can the control strategy incorporate the real-time behaviour.

5. FULL SCALE APPLICATION OF EQUALIZATION

Quantitative evaluation of the benefits to be derived from flow equalization has been restricted, almost exclusively, to the effect

on (1) primary sedimentation and secondary clarifier performance (on the basis of effluent TSS concentration), and (2) biological process performance (on the basis of effluent BOD concentration). The most extensive analysis on equalization performance has been compiled by Ongerth (1979); the survey considers 147 equalization facilities located throughout the U.S.A. To identify and assess the magnitude of equalization effects on unit process and treatment plant performance probability plots of average daily observations are used. As a baseline for evaluating plant performance, data from a statistical analysis of the operation of 27 activated sludge plants provides a comparison (Hovey *et al*, 1977) (see Fig 2.15).

5.1 Primary Sedimentation Performance

In primary sedimentation flow equalization has been shown to result in improved performance and a more uniform primary effluent quality

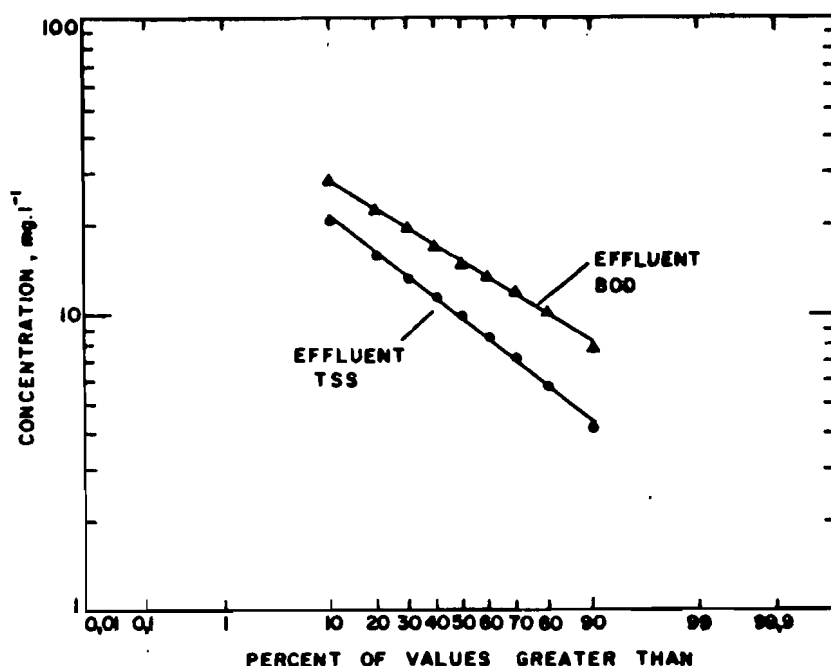


Fig 2.15 Distribution of log effluent concentrations for 27 activated sludge plants designed to meet EPA secondary treatment requirements (after Ongerth, 1979).

by Ongerth (1979) and other authors. A constant influent feed rate avoids hydraulic disturbances in the sedimentation basin created by (1) sudden changes in the influent flow rate and (2) surges caused by additional wastewater lift pumps coming into operation. La Grega and Keenan (1974) investigated the effect of flow equalization on a $6,8 \text{ Ml.d}^{-1}$ WWTP. An existing aeration tank was temporarily converted to an equalization basin and a comparison was made between plant performance under normal operating conditions and when flow equalization was employed. From the investigation it was evident that the primary sedimentation basins were markedly more efficient under equalized flow conditions than under normal conditions. The results are shown in Table 2.2.

Table 2.2 Effect of Flow Equalization on Primary Settling (after La Grega and Keenan, 1974).

Item	Normal Flow	Equalized Flow
Primary influent SS, mg/l	136,7	128
Primary effluent SS, mg/l	105,4	68
SS Removal, %	23	47

Location of equalization tanks *upstream* of primary clarifiers provides optimum conditions for clarifier operation; however it is necessary to (1) prevent excessive solids accumulating on the floor of the equalization tank and (2) maintain aerobic conditions in order to avoid odour problems. Both these requirements can be achieved conveniently in the equalization basin by installing either mechanical or bubble aerators. Pre-aeration, in fact, may lead to a further improvement in primary sedimentation performance due to enhanced flocculation (EPA, 1974). This has been demonstrated by Seidel and Baumann (1961). However, if centrifugal pumps transfer the flow from the equalization basin to the primary sedimentation basin the beneficial effect of flocculation brought about by aeration may be diminished.

5.2 Secondary Clarifier Performance

In secondary sedimentation flow equalization may be expected to have an even greater impact on performance than in primary sedimentation. The improvement in performance is derived from the smoothed hydraulic loading and the consequential reduction of variations in solids loading on the settler. In plants where the settler is overloaded for a portion of the day flow equalization will result in reduced effluent suspended solids concentrations and allow increased throughput. In plants receiving the full diurnal flow variation the secondary settlers must be designed to handle the peak flow rate - with flow equalization the secondary settling tanks need to be designed for a substantially reduced flow rate.

In existing plants where nitrification is an objective flow equalization has an added advantage in that the problem of denitrification associated with sludge accumulation during cyclic high-flow periods is minimized. Also, it is likely that the flow to the plant can be increased without additional provision of settling capacity, or, the process be operated at longer sludge ages if greater efficiency of nitrification is needed.

Despite expectations, data reported in the literature does not indicate major improvements in secondary clarifier performance with flow equalization. For example, at the Walled Lake/Novi plant Foess, Meenahan and Harju (1977) observed virtually no difference in secondary clarifier effluent between the equalized and unequalized flow periods. It was concluded that the reason for the lack of observable difference was that, over the testing period, the secondary clarifiers were appreciably underloaded, and hence a full demonstration of the effects of flow equalization was not possible.

A similar lack of improvement in clarifier performance was observed with "in-line" flow equalization at the Ypsilanti, Michigan, plant by Foess, Meenahan and Blough (1977). They demonstrated that the standard loadings on clarifiers are overly conservative: by increasing hydraulic loading from the chosen standard of $32,8 \text{ m}^3 \cdot \text{d}^{-1} \cdot \text{m}^{-2}$ to $47,5 \text{ m}^3 \cdot \text{d}^{-1} \cdot \text{m}^{-2}$ performance was unchanged.

Because of the general overdesign of secondary settling tanks the consequential lack of improvement of effluent quality with flow equalization has caused some investigators to conclude that flow equalization was not worthwhile. However, by eliminating peak flows, and designing secondary clarifiers on the basis of the average flow criteria, a considerable reduction of tank size should be possible without affecting effluent quality. Conversely, in cases where secondary clarifiers are overloaded under cyclic flow conditions, flow equalization should allow increased throughput, with improved effluent quality.

5.3 Biological Process Performance

Depending on the extent of flow equalization and the volume of the equalization basin, a certain measure of attenuation of concentration variations, and consequently mass loading variations, will result. Speece and La Grega (1976) postulated that, because of the capacity of activated sludge to absorb COD shock loads, load equalization will not result in a significant improvement in effluent COD quality. This hypothesis is supported by the many results presented by Ongerth (1979) which generally show only a minor improvement in effluent BOD from periods of unequalized to periods of equalized flow. The insensitivity of effluent COD to influent loading patterns is explained by Ekama and Marais (1978) in that (1) soluble biodegradable COD is rapidly utilized and is usually not present in the effluent, and (2) particulate COD is enmeshed in the sludge mass prior to adsorption, and hence, also does not appear in the effluent. In this fashion the effluent COD becomes in a sense independent of the influent load and biological activity of the process.

While the insensitivity is true as regards the COD, the same does not apply to the response of the activated sludge process incorporating nitrification-denitrification. For these plants Wilson and Marais (1975) found that both variable flow *and* variable load conditions have a definite detrimental effect on the effluent TKN and nitrate concentrations, as shown in Fig 2.16. The reason for this lies in the kinetics of nitrification: The mass of nitrifiers in the process is fixed by the mass of TKN entering the plant and

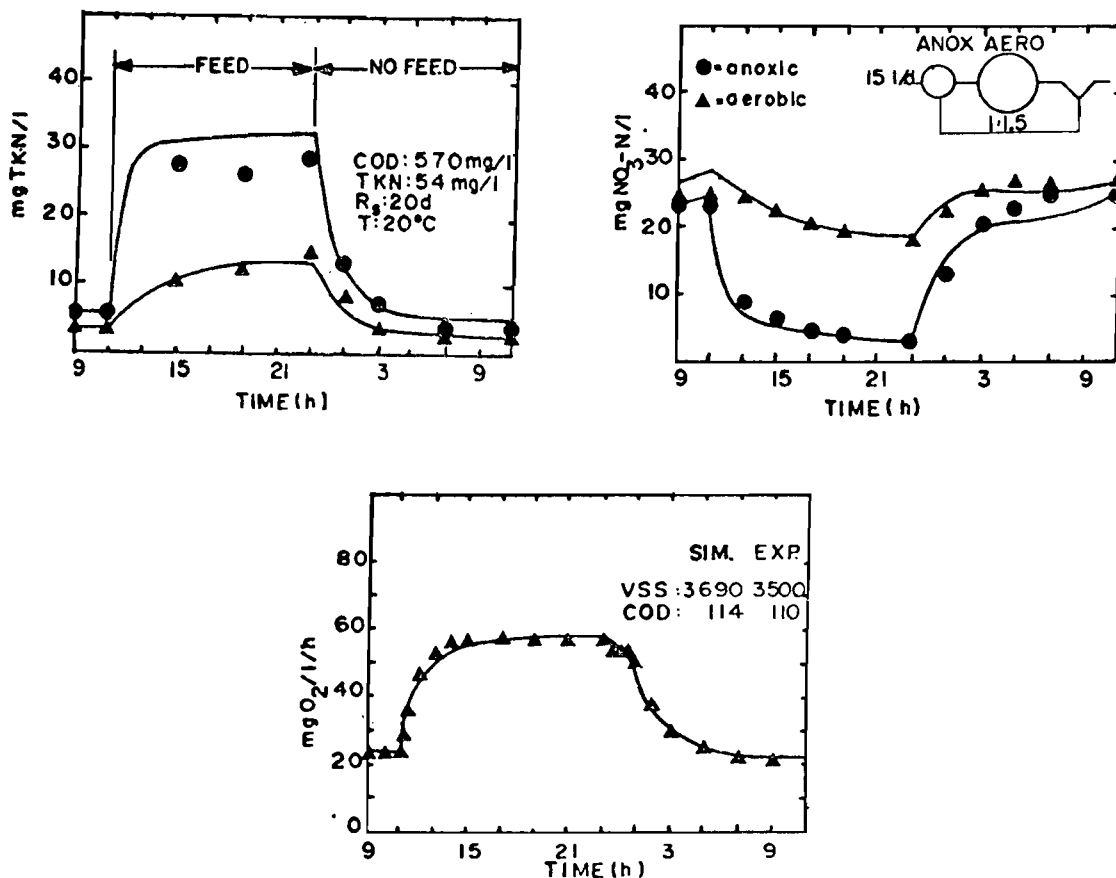


Fig 2.16 Observed and predicted TKN, nitrate and oxygen utilization rate response profiles in a series reactor configuration under square wave loading conditions, with the first reactor unaerated (1,0l) and the second aerated (6,4l). (after Van Haandel and Marais, 1981).

the sludge age. In nitrification no adsorption and storage effects are present; during the high flow/load period under cyclic flow and TKN load conditions the rate of nitrification, even though at its maximum, may be insufficient to nitrify the ammonia at the rate it enters the plant, and ammonia appears in the effluent with a corresponding decrease in effluent nitrate concentration. The reduction in nitrification efficiency is most apparent when the sludge age is less than 20 percent greater than the minimum required for nitrification.

From the above discussion it is evident therefore that, with regard to effluent quality, the benefits of flow and load equalization are

minimal when evaluated on the basis of effluent COD (or BOD); however, in plants including nitrification the benefits may be substantial.

Although the COD effluent quality is essentially independent of the influent flow and load fluctuations the oxygen requirement for the plant is sensitive to the COD and TKN input *load* pattern; this is also illustrated in Fig 2.16. The fluctuation in oxygen utilization rate is not as severe as the fluctuation in load; adsorption of particulate COD and the slow utilization of this fraction tends to attenuate the response. The fluctuations in oxygen utilization rate are damped to approximately one third of that of the load. Despite this effect the fluctuation nevertheless requires that the oxygenation capacity must be at least equal to the peak oxygen demand, which increases plant capital costs. In addition, if running costs for provision of oxygen are to be minimized then the aeration intensity needs to be matched to the oxygen requirements over the day; this has generally been a difficult and costly exercise in itself. Load equalization obtained through flow equalization *per se*, therefore, will reduce both capital costs for aeration *and* the operational problems in matching the oxygenation intensity to the oxygen requirements.

5.4 Equalization Facility Operation

Very little information regarding the *operation* of flow equalization facilities has been reported in the literature. The most extensive investigation on full-scale application of flow equalization, that considers both plant operation and performance, has been presented by Foess, Meenahan and Harju (1977). They monitored the performance of the Walled Lake/Novi treatment plant under equalized and unequalized flow conditions. The schematic layout of the Walled Lake/Novi plant is shown in Fig 2.17. The layout includes an activated sludge process with additional treatment by trickling filter. Wastewater treated at the plant was primarily of domestic origin. Over the period of the investigation the average influent flows were higher during the months of January to May, indicating infiltration and storm water ingress problems. However, an infiltration and storm water inflow prevention program was in progress. As a consequence

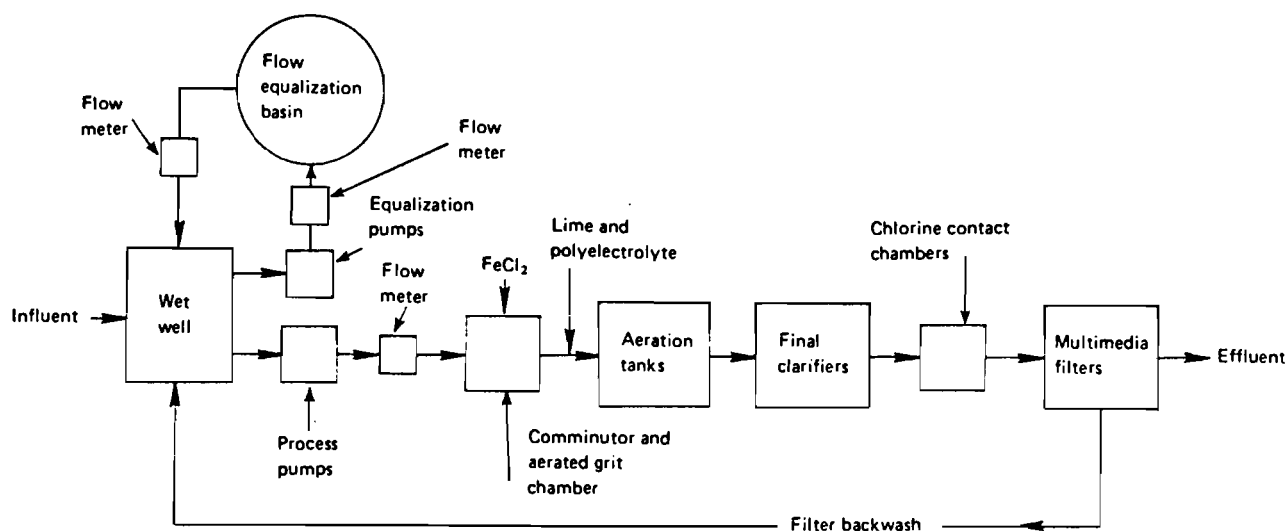


Fig 2.17 Schematic layout of the Walled Lake/Novi treatment plant, Michigan (after Foess, Meenahan and Harju, 1977).

these effects were reduced and became less prominent with time, indicating that the program was producing results.

Flow equalization was included in the plant design for the following reasons:

- (i) Constant rate filtration would provide a superior effluent to filtration under diurnally varying rates, for the same filter area;
- (ii) the cost of providing flow equalization would be nearly offset by savings derived from sizing the filters based on average, rather than peak, flow rates; and
- (iii) equalization would have a beneficial effect upon the activated sludge and final settling processes.

A "side-line" equalization system was selected in preference to an "in-line" one on the basis of pumping costs for the particular plant topography. The maximum storage volume of the equalization tank was set at 3,72 hour retention time, based on the average influent rate. The mode of operation for the equalization facility was flow "topping". Operation and control of the equalization facility was

as follows:

Each morning the average flow expected over the following 24 hours was estimated and the process pumps were pre-set to maintain this rate. When the flow increased above the process pumping rate a controller started an equalization pump to transfer the excess flow to the equalization basin. When the sewer flow to the wet well diminished to below average, an effluent control valve opened and released an amount of wastewater from the equalization basin to the wet well, to compensate for the deficiency of the influent sewer flow.

The authors reported that the control system functioned well and was capable of maintaining a virtually constant process flow rate. Initially the operators had difficulty in forecasting the average daily flow rate, necessitating frequent and excessively large adjustments to the process pumping rate, but with experience, control of the flow became efficient.

No information is given as to the success of the manual method of operation during periods of excessively high or low mean daily flow rates. Furthermore, the variability of the mean flow rates is not reported. The investigators report that during the testing period (one week of equalized and one week of unequalized flow) the daily flows and wastewater characteristics remained virtually constant from day to day, indicating a very regular pattern of flow. The reason for this regularity is probably a result of the sewage flow being derived primarily from a domestic source. It seems likely that over the whole period of the investigation the flow variation from one day to the next was very small, and this probably aided the estimation of the mean flow for each day. It is difficult, therefore, to judge in what manner the flow regulation would have been successful if the random daily variation of the mean flow had been large.

One important conclusion that can be made from the operation of this facility is that effective regulation of equalization basin flows by manual control is dependent on the operator's ability to make a correct decision based on past experience. Decision making for the

manual control of equalization facilities on the basis of estimating mean daily flow rates can be expected to be more difficult where there are either (1) marked variations in the mean daily influent flow, or (2) appreciable changes in the diurnal flow pattern from day to day.

At the Walled Lake/Novi plant the design objectives were tested by monitoring plant performance for a two week period; one week with, and one week without flow equalization. A comparison was made on (1) secondary clarifier effluent quality and (2) tertiary filter effluent quality. Over the test period average inflow rates and sewage characteristics were reported to be virtually constant.

- (1) Secondary clarifier performance: Very little difference in effluent TSS concentration was observed because under both equalized and unequalized flows the clarifiers were under-loaded; this feature has been discussed in Section 5.2.
- (2) Tertiary filter performance: Improved filter effluent quality was realized with flow equalization. Although the mean effluent quality from the activated sludge process secondary clarifier remained unchanged, filter performance was generally improved under equalized flow operation, both in terms of average removal efficiency and variability of quality. Comparative figures of the loads in the effluent of TSS, BOD₅ and NH₃-N are given in Table 2.3.

Table 2.3 Filter Effluent Loads over one-week periods of Equalized and Normal Flow at the Walled Lake/Novi Plant (after Foess, Meenahan and Harju, 1977).

Parameter	Normal Flow		Equalized Flow	
	Load, kg	% Removal	Load, kg	% Removal
TSS	93	33	51	82
BOD ₅	103	52	60	61
NH ₃ -N	2,0	-	8	-

6. DISCUSSION AND CONCLUSIONS

6.1 Neglect of Load Equalization

One may wonder why load equalization has received so little attention compared to flow equalization. The following considerations are probably the main contributory factors:

- (a) In plant operation under variable flow conditions the obvious and explicit problems arise from hydraulic effects, in particular with regard to primary and secondary settling tank efficiency and failure.
- (b) Inadequate parameters have been selected as criteria for evaluating the effects of load equalization. The principal parameter has been the BOD (or COD) concentration in the effluent. In terms of the effluent BOD very little benefit appears to be derived from load equalization either in terms of the average concentration or in its variability. Where differences have been noted these appear where the secondary clarifier was overloaded; during periods of high flow increased concentrations of particulate matter escaped over the weirs, i.e. the deterioration in effluent quality was due to inadequate provision of settling tank area.

With adequate settling capacity the insensitivity of the effluent BOD to load variations has been discussed already in Section 5.3; it was shown that the insensitivity arises principally from flocculation of particulate COD, enmeshment in the sludge mass and storage on the organisms. The effluent COD, therefore, is not an appropriate parameter for assessing any beneficial effects of load equalization.

A parameter more appropriate than the effluent COD is the oxygen utilization rate (OUR). The OUR has been identified by Marais and co-workers as one of the most sensitive parameters to unravel the kinetic response of an activated sludge plant. This is because the OUR is directly linked to the biological activity in the process.

At long sludge ages, because the mass of organisms is large with respect to COD load, i.e. the food/micro-organism ratio is small,

the COD load entering the process at any time is virtually immediately utilized. In consequence the OUR follows the load rate pattern closely. This is clearly illustrated in Fig 2.18 for a plant operated at 20 day sludge age under square wave flow and COD load conditions at 20°C. Note the appreciable fluctuation in oxygen demand; in contrast, the effluent COD remains virtually constant.

In Fig 2.19 the response of a plant, also under square wave flow and load, but operated at a 2.5 day sludge age at 12°C, is shown. The OUR now shows only slight variation despite the wide variation in load; this is due to the high food/micro-organism ratio. Although the biological activity per unit mass is at its maximum during the feed period the rate of utilization of material is not sufficient to utilize all of the COD entering the process and there is a build-up of stored COD during the feed period. Consequently, after the feed stops the organisms continue to utilize the stored COD for a considerable period subsequent to feed termination, still at the maximum rate. Hence, at short sludge ages the OUR also becomes relatively insensitive to the influent load variation. This observation leads to a third reason why load equalization has been partially neglected.

- (c) The effects of load equalization have generally been assessed in plants operated at short sludge ages. In the USA (where most of the research on equalization has been reported) the main concern hitherto has been removal of COD; for this purpose operation of plants at short sludge ages is adequate, and hence the importance of load equalization has been masked. In fact, when the sludge age is short, it is to be doubted whether load equalization can serve a useful function. However, for processes at long sludge ages load equalization can lead to substantial benefits: not only will the peak oxygenation requirement be reduced; oxygenation control will also be radically simplified. The latter aspect will be particularly appropriate to nitrification-denitrification-phosphorus removal systems where control of dissolved oxygen concentration assists in optimizing nitrogen

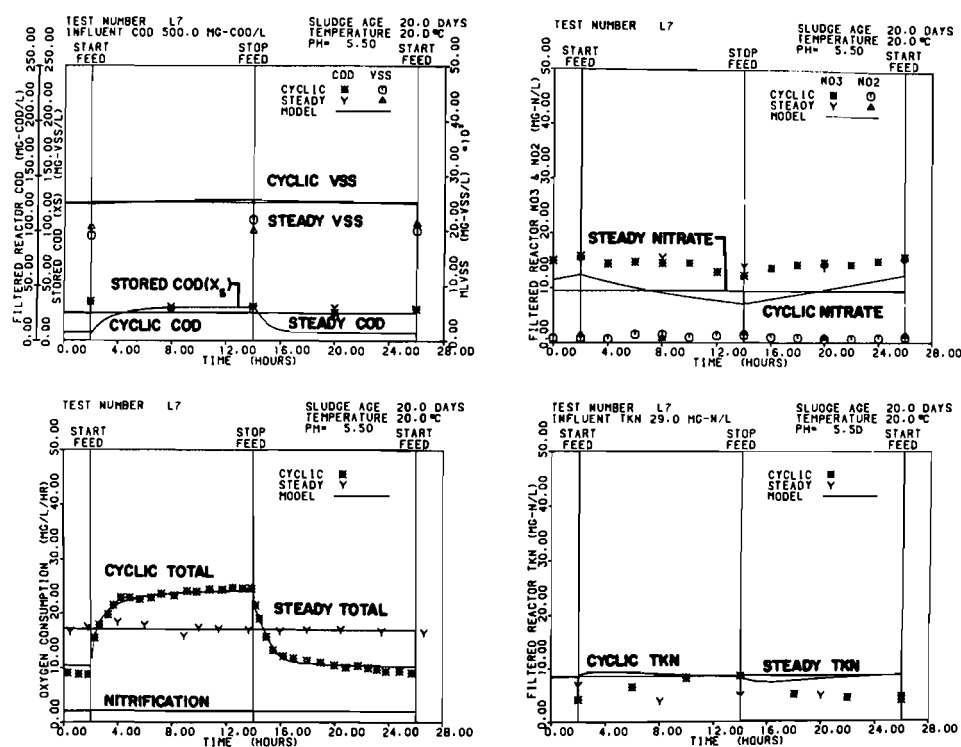


Fig 2.18 Response of a single reactor activated sludge plant under cyclic flow and load conditions (12 hours feed/12 hours no feed) operated at a 20-day sludge age.

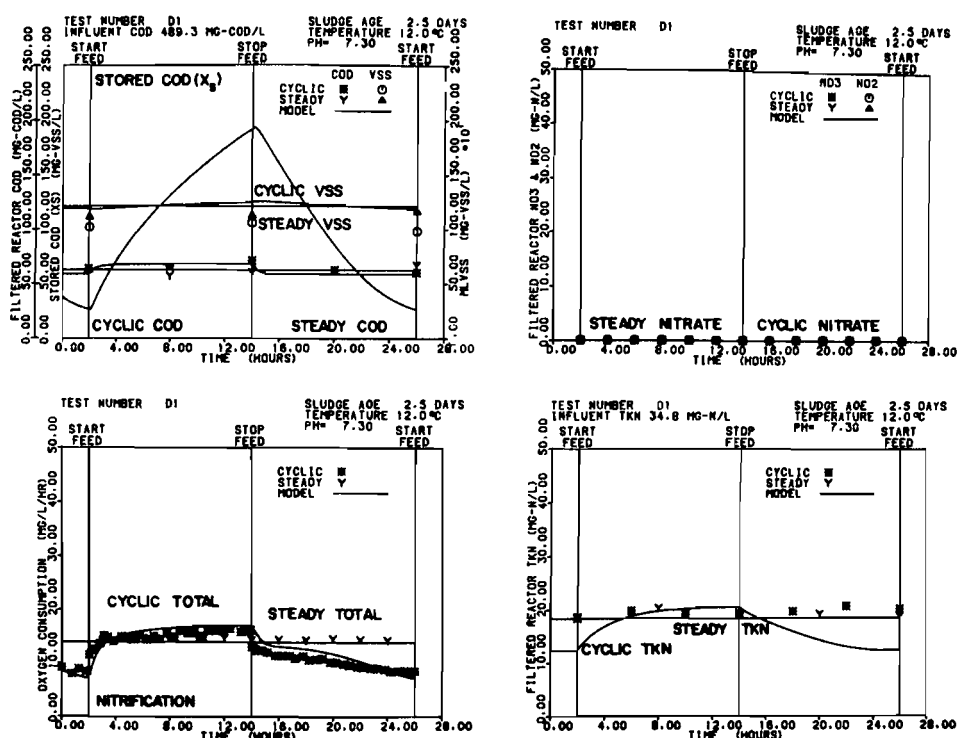


Fig 2.19 Response of a single reactor activated sludge plant under cyclic flow and load conditions (12 hours feed/12 hours no feed) operated at a 2.5-day sludge age.

and phosphorus removal and maintaining reasonable sludge settling characteristics.

6.2 Conclusions

Conclusions from the critical discussion of the status of flow and load equalization with regard to its application in wastewater treatment plants are:

- (1) Equalization of inputs to a treatment plant involves equalizing flow and/or load. Equalization of flow contributes to attaining improved utilization of those processes dependent on hydraulic characteristics; particularly primary and secondary settling tanks. Equalization of load contributes to enhanced plant operation through smoothing out the biological activity in the plant; benefits from load equalization are generally obtained at long sludge ages where:

- attenuation of oxygen utilization rate is achieved, leading to simplified plant control
- peak oxygen demand is reduced, thereby reducing capital costs for providing the aeration capacity required to match the peak requirement
- plants incorporating nitrification, denitrification and phosphorus removal exhibit less variability in effluent ammonia and nitrate concentration; in addition, load equalization will provide considerable assistance in maintaining the optimal removal of the nutrients, nitrogen and phosphorus.

At short sludge ages load equalization has little benefit; the storage mechanism in the biological process automatically results in attenuation of OUR.

In general effluent COD quality is unaffected by flow and load fluctuations due to the mainly particulate nature of the influent COD which is physically removed from the effluent flow by enmeshment and adsorption on to the active mass.

- (2) Constant volume equalization contributes only in a limited degree to load equalization: even should complete attenuation of

concentration variations be possible there still remains a load variation equal to the flow variation. Therefore, if flow variations are large, constant volume equalization has little merit because it does not improve process performance with respect to either OUR attenuation or hydraulic effects.

- (3) The design of an equalization facility involves not only the sizing of the equalization tank, but also the provision of an operating strategy to ensure that the desired objectives are met. This includes:
- Effective equalization of flow and/or load while not exceeding the physical volume limits of the particular equalization tank.
 - Incorporation of the effects of changing influent patterns both on a seasonal basis and from weekday to weekend.
 - Manages deviations from "normal" behaviour (e.g. storm flows) optimally.
- (4) The major difficulty encountered with variable volume equalization appears to arise from a lack of an efficient operating strategy. In particular, where human judgement is employed to control outflow rate, experience and skill is required, at best it appears unlikely that a high level of efficiency can be achieved in this manner of operation.

It is apparent from the review of the present status of equalization that enquiry is needed not only into the design of these facilities but also into methods of improving operation and control procedures. With regard to operation and control, evidently alternative approaches to manual procedures merit study. The control problem cannot be resolved by the standard procedures of feed-back or feed-forward control alone - the nature of the problem necessitates some form of "intelligent" control strategy which requires the incorporation of extensive computational facilities. There is good reason to believe that by using a microprocessor to control the operation of an equalization facility most, if not all of the problems associated with manual operation can be overcome, and optimal performance of the plant

attained with respect to attenuation of the influent flow and load fluctuations encountered in practice. No reports could be found in the literature in which this approach has been suggested for the control of equalization tanks - however, it seems to be the logical one, and is being exploited in many process control applications.

CHAPTER THREE

DEVELOPMENT OF AN EQUALIZATION ALGORITHM

1. INTRODUCTION

In Chapter 2 it has been demonstrated that both flow and load equalization can have many beneficial effects on wastewater treatment plant operation and control. However, it was also evident that exploitation of the full potential of equalization facilities has yet to be achieved because no adequate means has been available whereby the facility can be effectively controlled to give optimal performance under the real-time conditions of variable daily cyclic flow rate, concentration and load.

To solve the problem of achieving optimal equalization it is necessary to set out the objectives for equalization, and the constraints within which optimization of these objectives are to be achieved. Three possible objectives can be set down for equalization:

- (1) Flow equalization
- (2) Load equalization
- (3) Flow and load equalization.

These particular objectives have been selected because of the advantages that have been discussed in Chapter 2. Other objectives could have been selected; for example, equalization of concentration. However, a little reflection will show that there is no advantage in this parameter over that of load because the oxygen demand and process response of the downstream plant is controlled by the load (i.e. concentration x flow rate) and not by the concentration *per se*.

Flow and load are not independent of each other because, as we have noted above, load is the product of flow rate and concentration. For this reason effective equalization of either one, of flow or load, necessarily brings about a concomitant attenuation of the other. This can be seen as follows: Assume a tank has a certain hold-up at some instant; if the tank is completely mixed then mixing of the influent flow and concentration with the tank contents necessarily will attenuate the

tank *concentration* to a lesser variability than that of the influent identical to the case with constant volume equalization. The degree of attenuation will be determined by the ratio of tank hold-up to through-flow rate. The *load* in the tank effluent will now tend to vary more in keeping with the flow than would have been the case if no hold-up was interposed in the influent line. However, by keeping the tank hold-up constant, no *flow* equalization is achieved; consequently, at best the variation in effluent load will be the same as that of the flow. If, in addition, the tank hold-up is allowed to vary, and if this is done appropriately, a large measure of *flow* attenuation also can be achieved. This, together with the attenuation of *concentration* due to the mixing action described above, will bring about a large degree of *load* attenuation also. Variable volume equalization, therefore, would appear to be the only means whereby flow equalization is possible with an associated measure of load equalization.

Complete equalization of flow does not necessarily result in complete equalization of load because the influent patterns of flow and load are not identical. However, it will be shown later that, by allowing slight deviations from optimal flow equalization over parts of the cycle, a disproportionate equalization effect on the load fluctuation can be achieved. Consequently, if optimal equalization of both flow and load is set as the objective, the equalization for both will not be as good as when either the one or the other is equalized optimally.

We have seen that in achieving flow attenuation there is always an associated attenuation of load, i.e. flow and load attenuation are not independent of each other. How can one approach optimal attenuation of both flow and load? Basically one needs to combine flow and load in some quantitative fashion to achieve this. Later in this Chapter this aspect will be discussed in greater detail; briefly the approach is as follows:

For a given tank size, under fixed cyclic input patterns of flow and load, a specified outflow profile over the cycle will also have an associated effluent load profile. The deviations in the effluent profiles over the cycle from their respective mean values are then used to quantify two error components (one

for flow and one for load) which then provide a measure of the "goodness" of the attenuation of the two parameters. The two errors are added together and the procedure for obtaining optimal equalization of flow and load is to minimize the total error by suitably modifying the outflow pattern over the cycle (and therefore also the load pattern).

By forming the sum of the error components the approach above allows a "weight factor" to be applied to the respective flow and load components of the error. Applying a weight factor has the advantage that it gives the freedom to assign relative levels of importance to flow and to load as required by the objectives set for equalization, and to optimize flow *and* load equalization within this constraint. In fact, using this approach, equalization of flow or load alone becomes a subset of simultaneous flow and load equalization by assigning all the weight to either flow or to load.

The description above identified one constraint to be satisfied in optimizing the equalization action; other relevant constraints that are immediately apparent are:

- the equalization tank volume available
- the possible existence of a minimum allowable tank volume level
- the tank should neither overflow nor be drawn down to a level below the minimum.

Some other minor constraints will become apparent later.

Within the constraints set out above the essence of the problem of equalization is:

Under the cyclic inputs of flow and load, determine the appropriate outflow rate at any time such that the flow and/or load will be optimally equalized.

From the statement above it is evidently necessary to know the influent flow rate and concentration patterns over the ensuing 24-hour cycle in order to compute the outflow profile giving the "best" equalization of flow and load. This problem can be resolved

by breaking it down into two problems that need to be solved:

- (a) If the complete influent flow rate and concentration patterns for a 24-hour cycle are known, how is the outflow pattern for optimal equalization determined, taking due cognizance of the weight factors for flow rate and load, and the constraints that the tank should not overflow and underflow, and other minor requirements such as limiting the rate of change of outflow rate? The solution to this problem requires the development of a suitable *equalization algorithm*.
- (b) If the influent flow rate and concentration patterns and the mean flow and mean load per day are not constant from day to day, how are the patterns to be predicted, and how is this variability accommodated to achieve real-time optimal equalization? The solution to this problem requires application of the equalization algorithm in an appropriate *control strategy*.

In the present Chapter and in Chapter 4 the equalization algorithm will be developed and tested; Chapters 5 and 6 deal with the incorporation of the algorithm in a control strategy, and in Chapter 7 the implementation of the strategy at full-scale is discussed.

2. REQUIREMENTS FOR ALGORITHM

A necessary requirement for the development of a mathematical algorithm by means of which optimal equalized flow and load patterns can be determined is the existence of a quantitative measure whereby the relative success of a particular solution may be assessed. In this context a solution refers to one particular effluent flow rate profile over a cycle together with its associated effluent load profile (which is determined by the influent flow and load profiles and the equalization volume available). The effectiveness of a particular equalization solution may be *qualitatively* assessed by comparing the variations over a cycle (one day, in this case) of the equalization tank effluent flow and mass load rates, both about their respective mean values, with the corresponding variations of the influent. As indicated in the previous Section, *quantification* of these variations may be achieved by means of a suitable error expression. This error expression should take into

account (1) the size of the variations in both the flow and the load over the cycle, (2) the relative significance of deviations in flow as compared to load, and (3) other restrictions resulting from physical constraints such as the equalization volume available and possibly a limitation on the allowable rate of change of outflow rate.

Once any error expression is accepted the optimal equalization solution is also fixed. Judgement as to whether one error expression is superior to another must necessarily be subjective. In some instances an expression may be summarily rejected because it results in unstable operation, but strictly an absolute comparison of error expressions is not possible because in each case the resulting optimal solution must be assessed only in terms of the same considerations that entered into the formulation of the error expression used in attaining that particular solution. This holds true provided the solution procedure converges to the true optimum independent of the starting point of the solution.

The concept of an error expression also allows an assessment of the effect of various factors which influence the extent of equalization such as the form of the influent patterns and the size of equalization tank available. For example, given a particular set of influent flow rate and load profiles, the influence of tank size may be assessed by comparing the numerical value of the error expression for the optimal solutions for different tank sizes. Conversely, for a particular tank size, the effect of different influent profiles may be assessed by comparing the ratios of the optimal error expression to the value of the error expression calculated for the influent profiles.

The above discussion identifies two separate aspects which require attention in the development of an equalization algorithm:

- Development of an iterative procedure whereby, given some starting condition, optimal equalized flow and load patterns can be determined. This optimization procedure involves minimizing the numerical value of a selected error expression.
- Formulation of the error expression.

In discussing these two aspects there is no reason why one should be considered before the other because each is a separate entity. In this investigation the development of the iterative procedures will be dealt with first, accepting the existence of an error expression, and following that the formulation of the error expression is considered.

3. DEVELOPMENT OF ITERATIVE PROCEDURE

It is assumed that the variable on which control action will be taken in the operation of an equalization facility is the outflow rate from the equalization basin. For a given equalization configuration, mode of operation and tank size, under fixed diurnal input patterns of flow rate and load, a given tank outflow profile over the cycle will also have an associated effluent load profile; a specific value of the error expression may, in turn, be calculated from the effluent flow and load profiles. In determining the optimal situation, the approach adopted is to develop, subject to the particular constraints, a particular tank outflow profile which, together with its associated load profile, will minimize the numerical value of the specified error expression. The procedure for determining the optimal condition briefly may be described as follows:

To initiate the algorithm an arbitrary tank outflow profile is chosen. The associated effluent load profile and the associated value of the error expression are then calculated. The outflow profile is improved in the direction of the "best" profile by making successive small adjustments to the profile such that each adjustment causes a decrease in the value of the error expression. When incremental adjustments at any point in the outflow profile no longer result in the decrease in the value of the error expression, the profile is accepted as the optimum in terms of the criteria on which the error expression is based.

Before discussing how the individual incremental changes are made to the outflow rate profile, we consider the equalization tank response as this has a bearing on the discussion which follows.

3.1 Mathematical Analysis of Equalization Tank Response

3.1.1 Outflow Rate and Volume Response

The differential equation describing the relationship between inflow, outflow and tank volume response is derived from a material balance as follows:

$$\begin{aligned} [\text{Rate of flow into tank}] &= [\text{Rate of flow out of tank}] \\ &+ [\text{Rate of evaporation from tank}] \\ &+ [\text{Rate of accumulation in tank}] \end{aligned} \quad (3.1)$$

Considering the rate of evaporation to be negligible, Eq (3.1) can be written as:

$$F_o = F_l + dV/dt \quad (3.2)$$

Thus

$$dV/dt = F_o - F_l \quad (3.3)$$

where

V = tank volume

F_o = influent flow rate

F_l = effluent flow rate

t = time.

In this equation the influent flow rate, F_o , is, in the terminology of control systems, a "load variable", i.e. an uncontrolled variable which is set by external factors and whose variations must be accommodated by the control system. Of the other two variables, F_l and V , one may be freely manipulated, whereupon the behaviour of the second will be fixed by Eq (3.3). The analysis of tank response may therefore be approached in two ways:

- (i) Specify a tank volume profile over the day; knowing the influent flow pattern over the day, the effluent flow profile can be calculated, or
- (ii) Specify an effluent flow profile over the day; knowing the influent flow pattern, the tank volume profile can be calculated by integration.

Both approaches were investigated. It was found that using Approach (i) led to instability in determining effluent flow rates. The instability develops in situations of maximum or minimum tank volume, where the rate of change of tank volume becomes zero. In this case the necessary condition is that the effluent flow rate must equal the influent flow rate and this, in the incremental analysis, caused the instability. Application of Approach (ii) did not lead to instability, and hence was used in further development.

3.1.2 Concentration Response

Once the flow and volume behaviour is established the associated effluent concentration profile (and consequently an effluent mass loading profile) can be derived from a material balance on mass of organics, assuming completely mixed conditions in the tank:

$$\begin{aligned}
 [\text{Rate of mass flow into tank}] &= [\text{Rate of mass flow out of tank}] \\
 &+ [\text{Rate of mass removal by bio-} \\
 &\quad \text{logical reaction}] \\
 &+ [\text{Rate of mass accumulation in tank}]
 \end{aligned}
 \tag{3.4}$$

In this study the rate of mass removal by biological reaction will be assumed negligible. Thus:

$$\begin{aligned}
 F_o C_o &= F_l C_l + d(C_l V)/dt \\
 &= F_l C_l + V(dC_l/dt) + C_l(dV/dt)
 \end{aligned}
 \tag{3.5}$$

where

C_o = influent concentration

C_l = tank concentration (effluent concentration).

Substituting for dV/dt from Eq (3.3):

$$F_o C_o = F_l C_l + V(dC_l/dt) + C_l(F_o - F_l) \tag{3.6}$$

Thus:

$$dC_l/dt = F_o(C_o - C_l)/V \tag{3.7}$$

Equations (3.3) and (3.7) may be approximated by finite difference,

respectively, as:

$$V_t = V_{t-1} + (F_o - F) \Delta t \quad (3.8)$$

and

$$C_t = C_{t-1} + F_o(C_{o_t} - C_t) \Delta t / V_t \quad (3.9)$$

where

V_t = volume of tank at time t

V_{t-1} = volume of tank at time $(t-1)$ i.e. $t - \Delta t$

Δt = length of time interval

F_o = mean influent flow rate from $(t-1)$ to t

F = mean effluent flow rate from $(t-1)$ to t

C_t = tank concentration at time t

C_{t-1} = tank concentration at time $(t-1)$ i.e. $t - \Delta t$

3.2 Optimum Tank Outflow Rate Profile

The diurnal equalization tank effluent flow rate profile is developed using an iterative procedure which gradually improves the outflow rate profile in a step-by-step fashion until, in terms of the specified error criterion, no additional improvement can be made. The method by which successive changes are made to an existing outflow profile in the iterative procedure constitutes the *equalization algorithm*, and is discussed in detail below.

3.2.1 Initiating the Outflow Profile Development

In the interests of generality, the values of the equalization tank outflow and inflow rates are normalized, i.e. expressed as fractions of the mean flow rate.* Assuming a specified 24-hour normalized influent flow rate pattern to the WWTP, the influent flow rate pattern to the equalization tank will be determined by the configuration and method of operation of the equalization system. In this analysis, for the purposes of illustration, an "in-line" configuration, where all the influent flow passes to the downstream process via the equalization tank, has been selected. It is also assumed

* In the rest of this report, except where stated otherwise, the flow rates will be expressed in normalized form.

that the equalization tank volume is fixed. This volume is specified in terms of the tank retention time, based on the mean influent flow rate.

In the numerical procedure the tank outflow profile is subdivided into N intervals over the course of the day. Over each interval the flow rate is assumed to change linearly from the value at the end of the previous interval to that at the start of the subsequent interval. An arbitrary initial outflow rate profile over the day is chosen. In the absence of information on the outflow rate profile the simplest initial profile is one having a constant value of 1.0 over the day, i.e. the initial chosen tank outflow rate over each of the N intervals is equal to the mean normalized influent flow rate. Assume N is assigned a value of 12, i.e. the outflow profile is made up of 12 linear portions, each spanning a 2-hour period ($24/N$ hours). This profile is shown as a solid line in Fig 3.1. The procedure continues as follows:

Using the chosen outflow profile, together with the known normalised influent flow rate pattern, and a given starting value of the tank hold-up (expressed as a percentage of the total volume) at time 0, integration of Eq (3.3) provides the associated diurnal tank volume profile. This volume profile, together with the influent and effluent flow rate profiles and a specified value of the tank concentration (e.g. COD) at time 0, in turn allows a tank concentration profile for the day to be calculated by integration of Eq (3.7). Consequently, the associated effluent COD mass loading profile for the day can be calculated.

Based on the volume, effluent flow and load profiles, the value of the error expression is calculated and stored, to provide a comparison after changes are made to the existing tank effluent flow rate profile.

3.2.2 Mechanism for making a Single Change to Outflow Rate Profile

The mechanism by means of which a single change is made to the existing tank outflow rate profile, at a specified time interval, is laid out step-wise.

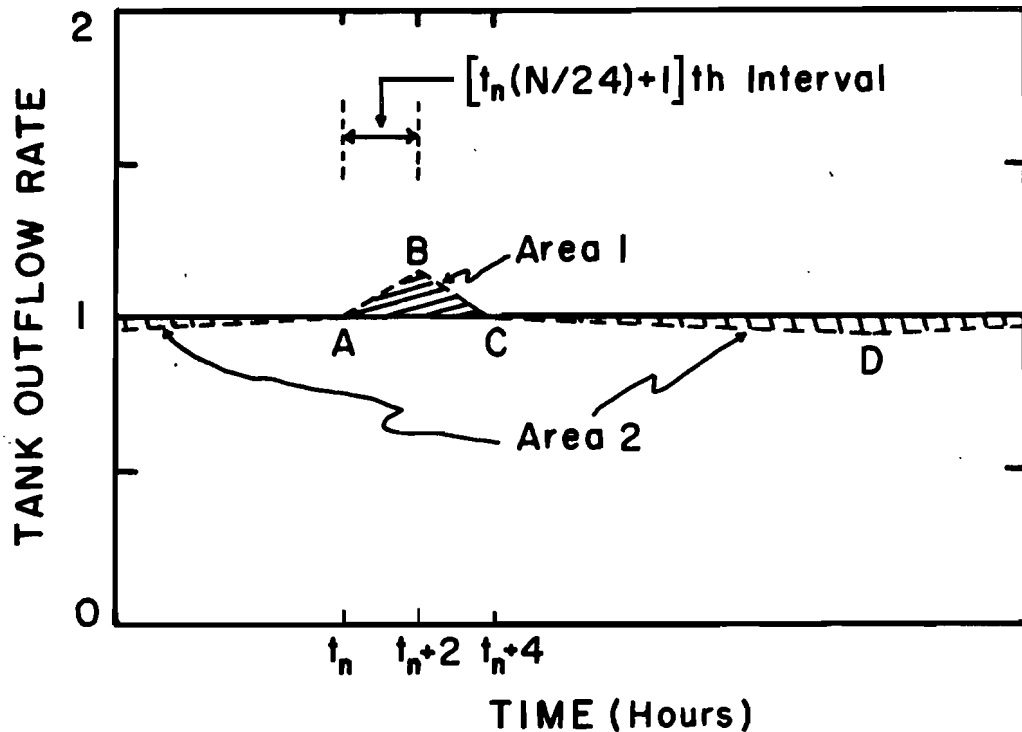


Fig 3.1 Method of adjustment of the outflow profile.

Step 1 : Identify the interval under consideration. Assume that the interval is that from time t_n to time $(t_n + 24/N)$, in this case time $(t_n + 2)$ in Fig 3.1. This is the $[t_n(N/24) + 1]$ th interval in the day. The flow rate at the end of the interval is either increased or decreased, as required, by an amount DELTA (an increase is illustrated in this case).

Step 2 : Increment the flow rate over this interval linearly from point A (the beginning of the interval) to point B (the end of the interval), where the increment at point B is DELTA.

Step 3 : Decrement the flow rate linearly from that at point B (the end of the interval) to the existing flow rate at point C (the end of the *next* interval).

Step 4 : Make an adjustment to the outflow rate profile in order to

maintain a material balance, i.e. to ensure that the mean outflow over the day remains at 1,0. The effect of Steps 2 and 3 is to increase the outflow rate over two intervals from time t_n to time $[t_n + 2*(24/N)]$, in this case $(t_n + 4)$. To maintain a material balance the incremental flow volume must be decremented over the remaining $(N-2)$ intervals. The method used is to linearly decrease flow rate from point C to the midpoint of the remaining $(N-2)$ intervals, i.e. $(N-2)/2$ intervals forward of point C, in this case $(12-2)/2 = 5$ intervals of 2 hours, i.e. 10 hours forward of time $(t_n + 4)$, to point D; then increase linearly from point D back to point A. The exact decrement at point D depends on DELTA, and is chosen to satisfy the material balance, i.e. Area 1 equals Area 2 in Fig 3.1).*

The dotted line in Fig 3.1 represents the tank outflow rate profile resulting from one change to the existing profile, made at the $[t_n(N/24) + 1]$ th interval. With this new outflow profile new tank volume and effluent mass loading profiles are calculated, and hence a new value of the error expression is calculated.

A comparison of the new error value with the old value allows an assessment of the two outflow profiles in terms of the error expression. If the new error value is smaller than the previous value, then the new outflow rate profile has resulted in improved equalized effluent flow and loading profiles. If not, a change in the opposite direction may be made. If this results in an improved error the change is accepted, or otherwise the original profile is retained and a move to the next interval is considered.

3.3 Equalization Algorithm

3.3.1 Optimization by Method of Steepest Descent

The discussion in the previous section described how a single change can be made at a specified interval in the tank outflow rate profile,

*This adjustment technique is but one of a number that can be used to distribute the flow adjustment arising from a change in flow rate over the interval under consideration. It was adopted as it appears to function satisfactorily.

and what effect it has on the tank outflow rate profile. In developing the optimal tank outflow rate profile a number of such incremental changes may be required. The procedure by means of which these successive changes are selected constitutes the equalization algorithm.

In Section 2.3.1 the tank outflow rate profile was subdivided into N intervals of equal length. An evaluation of the effect of an increase or a decrease in the outflow rate profile at each of these N intervals results in up to $2N$ different values for the error expression. By implementing the change that causes the maximum reduction in the magnitude of the error expression an optimal rate of convergence to the optimal tank outflow rate profile may be achieved. Utilization of this approach is analogous to the Method of Steepest Descent in multi-dimensional optimization problems. Consequently, this approach was adopted.

For completeness the step-wise procedure is set out in detail, even though certain aspects treated previously are repeated.

Step 1 : Select an arbitrary initial tank outflow rate profile. The tank outflow rate profile is made up of N linear portions, each spanning an interval of $(24/N)$ hours, with $n = 1, 2, \dots, N$ being the interval numbers.

Under the specified influent flow and load patterns the associated volume and effluent mass loading profiles are calculated. From the equalized effluent flow and mass loading profiles a value for the error expression is calculated.

Step 2 : To evaluate the effects of individual changes at each interval in the outflow rate profile commence with the first interval ($n = 1$).

Step 3 : Select the direction of change (increase or decrease) to the outflow rate profile in the same direction as the change which led to an improvement at this interval during the previous cycle. (Where the interval is being considered for the first time the change can be made in either direction).

Step 4 : Make a change to the outflow rate profile in the selected direction, utilizing the method described in Section 2.3.1.

From the new outflow rate profile, together with the influent flow and load profiles, calculate the associated tank volume and effluent mass loading profiles, as well as the value of the error expression, $E(n)$.

Step 5 : Compare the value of the error, $E(n)$, with the error value for the previous profile.

- (i) If the value of $E(n)$ is smaller than the error value determined for the previous profile, store both the direction in which the change is made, and the new value of the error, $E(n)$, in two temporary arrays (of dimension N), respectively. It is assumed that, if an improvement to the error is obtained in this step, it is not necessary to evaluate the error for a change in the opposite direction since such a change would inevitably lead to a worse error. Go to Step 6, to consider the next interval.
- (ii) If the value of the new error, $E(n)$, is larger than or equal to the error determined for the previous profile, reverse the direction in which a change in flow rate was made, and return to Step 4.
- (iii) If a change to the profile has been imposed in both directions, and neither has led to a value of $E(n)$ smaller than the error value for the previous profile, then we have a situation of "no change" at interval n . This is accommodated by assigning the value of the error for the previous profile to $E(n)$. Then go to Step 6, to consider the next interval.

Step 6 : If the value of n , the interval being considered, is equal to N , the last interval in the day, then the cycle of changes has been completed. Go to Step 7. Otherwise increment the value of the interval number n by 1 so that the next

interval can be considered, and return to Step 3.

Step 7 : The improvement in error that may be achieved by either increasing or decreasing the outflow rate at each interval has now been assessed. Considering the array of N error values $[E(1), E(2), \dots, E(N)]$, there are two possibilities:

- (i) If all the error values are equal to each other, and equal to the error value determined for the previous profile, go to Step 8.
- (ii) Otherwise, locate the interval in the day for which the lowest error value was obtained. This change is now incorporated into the profile, giving rise to a new tank outflow rate profile, with its associated error value. Repeat the cycle, returning to Step 2.

Step 8 : A change to the existing tank outflow rate profile at any of the N intervals, in either direction, does not lead to a decrease in the value of the error. No further improvement to the existing tank outflow rate profile is possible using the particular specified size of the discrete change (Δ).

Further improvement of the tank outflow rate profile may then be attempted by reducing the size of Δ and repeating the procedure from Step 2.

3.3.2 Optimization by Fast Convergence Approach

The Steepest Descent Method for the development of the optimal tank outflow rate profile requires a large amount of computation. If, for example, the outflow rate profile is divided into 48 half-hour intervals (a division that gave satisfactory results), then, before an optimal incremental (or decremental) change to the profile is selected, between 48 and 96 individual changes to the same profile have to be evaluated. Each evaluation involves adjusting the outflow rate profile, calculating the associated volume profile and the effluent mass loading profile, and then calculating an error value. To obtain the volume, concentration and load profiles over the day by integration of Eqs (3.3 and 3.7), step lengths of 5 minutes have

been utilized in this study in order to reduce finite difference errors, i.e. 288 simulation intervals over the day. Because the Method of Steepest Descent involves making only optimal changes each time the outflow rate profile is adjusted it probably involves the least possible number of modifications to an initial profile in converging to the optimal solution. However, because so many preliminary profiles need to be calculated in order to identify the optimal change the method is inefficient. To decrease the amount of computation involved in converging to the optimal solution the Fast Convergence Approach was developed.

In the Fast Convergence Approach, when changes to the outflow rate profile in the N intervals are considered, the incremental (or decremental) changes are made sequentially at the N intervals. Whenever an incremental (or decremental) change at an interval results in a decrease of the error value that change is incorporated into the outflow rate profile, before moving to the next interval. That is, any change to the profile that leads to an improvement, even though not necessarily the optimal improvement to the existing profile, is incorporated in the profile before considering the next interval in the cycle. In this way up to N improvements can be made during each cycle instead of only the single optimum change.

The step-by-step procedure for the Fast Convergence Approach is laid out in detail below. Certain similarities exist between the two Approaches but a detailed comparison of the procedures will indicate the differences:

Step 1 : The procedure is identical to Step 1 for the Method of Steepest Descent. An arbitrary initial tank outflow rate profile spanning N intervals over the day is chosen, and the associated value of the error expression is calculated.

Step 2 : To evaluate the effects of individual changes in the outflow rate profile commence with the first interval ($n = 1$).

Step 3 : As for the Method of Steepest Descent. Select the direction of change (increase or decrease) to the outflow rate profile in the same direction as the change made at

this interval during the previous cycle. (Where the interval is being considered for the first time the change may be made in either direction).

Step 4 : Identical to Step 4 of the Method of Steepest Descent.

Make a change to the outflow rate profile in the selected direction, and calculate the new value of the error associated with this new profile.

Step 5 : Compare the new value of the error with that for the previous profile.

- (i) If the new value of the error is smaller than the error value for the previous profile, then "accept" the new profile. Go to Step 6, to consider the next interval in the cycle.
- (ii) If the value of the new error is larger than or equal to that for the previous profile then reject the possible change, and reverse the direction in which a change in flow rate was made. Return to Step 4.
- (iii) If a change to the profile has been imposed in both directions, and neither has led to a new error value smaller than the error determined for the previous profile then retain the old profile and go to Step 6, to consider the next interval.

Step 6 : If the value of n , the interval being considered, is equal to N , the last interval in the day, then the cycle of changes has been completed. Go to Step 7. Otherwise increment the value of the interval number, n , by 1 so that the next interval can be considered, and return to Step 3.

Step 7 : When each of the N intervals has been considered, two possibilities exist:

- (i) At least one change to the outflow rate profile during the cycle has been "accepted", resulting

in an improvement in the error value. In this case further improvements may be possible; repeat the cycle by returning to Step 2.

- (ii) If no changes at any of the N intervals have been "accepted" then the tank outflow rate profile cannot be further improved using the particular specified size of the discrete change (Δ). Further improvement of the profile may then be attempted by reducing the size of Δ and repeating the procedure from Step 2.

3.4 Stability and Equivalence of the Two Approaches

In evaluating the validity of the two Approaches in developing the optimal tank outflow rate profile, under the cyclic inputs of flow and load, four questions must be answered :

- (i) Is the solution, determined by the simple finite difference integration procedure, well behaved?
- (ii) Is the optimization procedure in each Approach stable?
- (iii) Does the optimization procedure of each algorithm in fact converge to the optimal solution?
- (iv) Do the two Approaches converge to the same solution?

(i) To check whether or not the solution set determined by the simple finite difference procedure is *well behaved* the calculation of the tank volume, concentration and load profiles, under specified influent and effluent flow rate profiles over the day, was performed with different integration step lengths. It was found that, with an integration step length of 10 minutes, the response became oscillatory, particularly at times in the daily cycle when the tank volume was close to zero. However, when a 5 minute integration step length was used the response was stable. When the step length was reduced from 5 to 2,5 minutes the solution did not change, being identical to within 0,1 per cent. It was concluded that the first order finite difference method of integration appeared compatible with the set of equations which requires solution, provided the step

length is less than that which produces an oscillatory response.

(ii) Enquiring into the *stability* of the optimization procedures in the two Approaches, respectively, two parameters were found to affect each Approach. These are (1) N , the number of linear portions (each spanning an interval of $24/N$ hours) into which the tank outflow profile is subdivided, and (2) the ratio of the magnitude of the incremental change in flow rate (Δ) to the length of the interval ($24/N$). Where the tank volume is small, say equivalent to a retention time of 2 hours (based on the average influent flow rate), then, if the tank outflow rate is held equal to the mean inflow rate and the inflow rate is sustained at twice the mean inflow rate, the tank can be filled from empty in 2 hours. Under these circumstances, unless the outflow rate profile is divided into intervals of a quarter-hour or less (i.e. $N \geq 96$), oscillation in the convergence to the optimal solution occurred. Similar behaviour was encountered, even for larger tank sizes, when the ratio of Δ to the interval length was greater than 0.10 normalized flow units/hour, i.e. $\Delta/(24/N) \leq 0.10$. (Equivalently, the constraint is that $\Delta \cdot N \leq 2.4$). Guidelines for the choice of values for Δ and N are given in Appendix B, where instructions for the use of the computer program for implementation of either Approach are given.

(iii) *Convergence to the optimal solution* was tested by initiating the optimization procedure with different values of the initial tank hold-up and checking whether the solution achieved in each case was the same. The procedure was performed utilizing the criteria for stable solution as set out in (i) and (ii) above.

The test was performed by starting the identical equalization problem (same equalization configuration, tank size, inputs, etc.) at different initial tank hold-ups of 90 and 10 per cent of the maximum tank volume, respectively. In both cases the optimal solutions obtained were identical (within 0.10 per cent). Applied mathematicians generally consider that if the same well behaved solution is obtained using different integration step lengths and different starting conditions, the optimal solution is valid.

(iv) The equivalence of the two Approaches in converging to the optimal solution was evaluated by utilizing each Approach separately to develop the optimal tank outflow profile for identical cases. Only insignificant differences were observed in the resulting optimal solutions. This was taken as evidence that the more efficient Fast Convergence Approach was valid.

4. DEVELOPMENT OF THE ERROR EXPRESSION

In the previous Sections (2.1 and 2.2) the mechanism was discussed for modifying the tank outflow rate profile and an error expression was used as the criterion for evaluating the progress to, and the optimal solution for the tank outflow rate profile. It is now the intention to develop the concepts on which the error expression is based, and to formulate an appropriate expression.

The objective in developing the error expression is to quantify the various factors that will contribute to "good" performance of the equalization facility. Requirements in this respect may vary from one plant to another, and may be incorporated into the error expression. For the purposes of this study, the following factors have been used in formulating the error:

- (1) Variations in the tank outflow rate and the effluent mass loading rate, from their respective mean values. A weighting factor has been incorporated to account for the relative importance attached to these two parameters.
- (2) A large penalty error is imposed when the physical constraints of the system are not obeyed, i.e. the upper and lower tank volume limits are exceeded.
- (3) A constraint has been imposed on the rate of change of the tank outflow rate.

Consideration will now be given to the formulation of the individual components of the error expression. In developing the error expression, a constant diurnal influent flow and load pattern has been assumed. Consequently the problem of variations in the mean flow and load rates is not addressed here. This problem will be

considered later, where a control strategy for the real-time operation of an equalization facility is developed.

4.1 Outflow Rate and Load Rate Equalization Error

The basic requirement of variable volume equalization is to minimize fluctuations of the tank outflow rate and effluent mass loading rate about their respective mean values (usually the arithmetic mean).

These two variables are interdependent as load is calculated as the product of flow and concentration. Therefore, in order to increase load at a point, the flow must be increased, and *vice versa*, but always subject to the constraint that the total flow and the total mass load through the plant per day must remain constant.

It is proposed that the equalization error expression should consist of a weighted sum of the individual flow and load errors, as follows:

$$E_e = \alpha E_f + (1 - \alpha)E_{ld} \quad (3.10)$$

where

E_e = total equalization error due to flow and load

E_f = flow equalization error

E_{ld} = load equalization error

α = weighting factor for flow relative to load equalization.

In each equalization error term, E_f and E_{ld} , the size of the *global error* is a function of the size of the *deviation* of the variable from its mean value integrated over the day. The error in the flow rate or load rate at a point may be taken as equal to, proportional to, or some other function, of the magnitude of the deviation. The choice of the relationship between the actual deviation and the formulated error is a subjective one, taking cognizance of the process response to a deviation. The problem may be illustrated by considering the two cases for which the forms of the two flow profiles, A and B, respectively, are shown in Fig 3.2.

In each case, the mean flow rates are equal; if the error is taken as proportional to the deviations, then the error integrated over

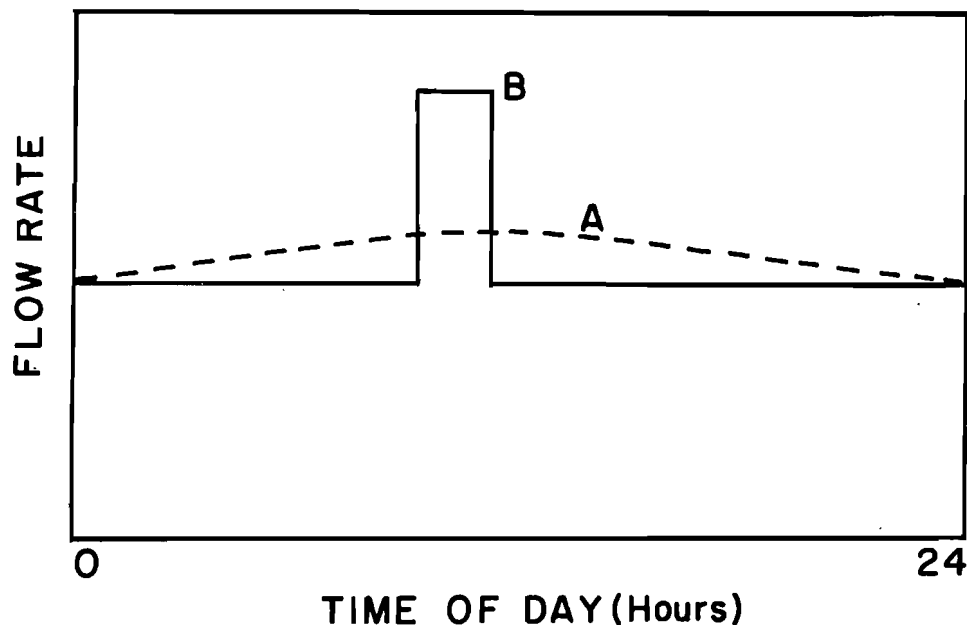


Fig 3.2 Effect of profile form on the formulation of the equalization error expressions.

the day is the same for both cases. However, the sharp peak in flow form B will have a greater adverse effect on downstream processes (e.g. settling tank) than A. Consequently, evaluation of the error from the deviation must take cognizance of the adverse effect of sharp deviations from the mean by ascribing a greater error value to form B than to form A. This can be achieved readily, for example, by taking the error as equal to the square of the deviation. Consequently it is proposed that the magnitude of the error at a point in the profile should be estimated as the square of the deviation of the normalized values from the mean. (The mean for normalized values will be 1.0 unit). To determine the global error, the error terms are integrated over the full 24-hour day. Thus, in numerical form, Eq (3.10) becomes:

$$E_e = \left\{ \alpha \sum_{i=1}^{n-1} (F/\bar{F} - 1)^2 \Delta t + (1 - \alpha) \sum_{i=1}^{n-1} (L/\bar{L} - 1)^2 \Delta t \right\} / (n-1) \quad (3.11)$$

where

F = tank outflow rate

\bar{F} = mean tank outflow rate

L = effluent mass loading rate

\bar{L} = mean effluent mass loading rate

α = weighting factor ($0 \leq \alpha \leq 1$)

n = number of simulation points over the day from 0h00 to 24h00, inclusive

Δt = integration step length [= $24/(n-1)$ h].

Because the outflow rate is taken into account in both the flow equalization error, E_F , and the load equalization error, E_{Ld} , the value of the weighting factor, α , is less sensitive to load variations than to flow variations. This may be considered a disadvantage in obtaining optimal solutions, but was accepted for the following reasons:

- (1) By utilizing this approach apparently very reasonable and acceptable solutions are obtained
- (2) The partial insensitivity to load variations is a desirable feature because, in a control strategy for the day to day (real-time) operation of an equalization facility, the direct measurement of flow rates over the day is readily achieved, whereas the direct measurement of influent COD concentrations over the day is either not feasible or involves considerable effort and expense.

4.2 Tank Volume Limit Penalty Error

In developing the optimal tank outflow rate profile by minimizing the equalization error the physical constraints of the system must be obeyed. That is, the optimal tank outflow rate profile must result in an associated tank volume (hold-up) profile which does not exceed the upper and lower tank volume limits at any time over the day.

With each adjustment of the tank outflow rate profile the associated tank volume profile is calculated. The adjustments to the outflow

rate profile are made on the basis of the value of the error expression. Therefore, the algorithm must contain a restraining factor that will not readily allow changes to the tank outflow rate profile such that the tank volume limits are exceeded. This is provided for by including a very severe penalty error that is added to the equalization error of Eq (3.10) when the volume limits are exceeded.* If the arbitrarily chosen initial tank outflow rate profile results in a volume profile that exceeds the tank volume limits, the high penalty error will strongly favour changes to the profile that will decrease the value of the total error by bringing the volume to within its limit constraints. Once the outflow rate profile results in the tank volume limits not being exceeded, the over-riding effect of the volume penalty error falls away. The algorithm is then principally involved with reducing the value of the equalization error by making changes to the outflow rate profile to decrease the value of the equalization error, without incurring the penalty error. It should be noted that, in the theoretical calculation procedure where an outflow rate profile is imposed on a particular equalization tank under a fixed input, hold-ups in excess of 100 per cent and less than 0 per cent of the tank volume might be calculated. Such situations do not pose a problem as they are strongly discouraged by the over-riding penalty error and do not appear in the final optimum solution.

The penalty error term for the volumetric limits consists of two parts; one for the upper and one for the lower volume limit. The extreme values for these limits (as a percentage of the total tank volume) are 100 and 0 per cent, respectively, but usually the normal limits of operation will be restricted to, say, 95 and 10 per cent. The lower normal limit will be dependent on (amongst other factors), the manner in which stirring is provided; if by floating aerators this limit will be influenced by the requirement that a minimum depth is needed for aerator operation, and so on.

* In developing the profile restrictions could be included which would prevent violations of volume limits. However, it is much more convenient to allow the algorithm to find its own optimum - the profile will be forced in the "right direction" by making the penalty for exceeding the volume limits very severe.

In formulating an expression for the volumetric penalty error a possible approach is to have a zero penalty when the tank hold-up is within specified limits and allocating a relatively large value to the penalty when the hold-up exceeds these limits. In implementing this approach, however, it was found that a discontinuous function of this nature at the prescribed limits causes instability in the development of the optimal tank outflow rate profile. It was found preferable to have a continuous penalty function that (1) has a value of zero for tank hold-ups within a certain range, δ_v , of the prescribed normal limit, (2) increases gradually as the limit is approached, and (3) increases rapidly as the limit is exceeded. These requirements are fulfilled by a power function of the form

$$E_{lm} = a n^b \quad (3.12)$$

where

E_{lm} = penalty error for tank volume limit

n = difference between the calculated tank hold-up at a point
and the hold-up δ_v within the volumetric limit

a, b = constants

The penalty error for the tank volume limits is formulated as follows:

Upper limit:

$$E_{lm} = \beta \sum_{i=1}^{n-1} \{V_p - (V_{lu} - \delta_v)\}^6 \quad (3.13)$$

for all i such that $V_p > (V_{lu} - \delta_v)$

Lower limit:

$$E_{lm} = \beta \sum_{i=1}^{n-1} \{V_p - (V_{lb} + \delta_v)\}^6 \quad (3.14)$$

for all i such that $V_p < (V_{lb} + \delta_v)$

where

V_p = equalization tank hold-up (as a per cent of total tank volume)

V_{lu} = upper normal tank volume limit (per cent)

V_{lb} = lower normal tank volume limit (per cent)

δ_v = volume differential within the limits at which E_{lm} attains a value (per cent)

β = a weighting factor (constant)

It was found that a value for δ_v of 5 per cent resulted in satisfactory behaviour. That is, if E_{lm} was assigned a value, starting from zero, when the tank hold-up was (1) equal to or greater than $(V_{lu} - \delta_v)$ per cent, or (2) equal to or less than $(V_{lb} + \delta_v)$ per cent. The factor β acts as a weighting factor of the importance of the tank volume limit penalty error relative to the other components of the equalization error. Stable convergence to the optimal solution was obtained when a value for β of 2.0×10^{-6} was used in all the cases considered in this investigation; it is likely that this value will suffice for any normal influent flow and load pattern. However, for possible cases where difficulty is experienced, guide-lines for the selection of the β value are given in Appendix B. The variation of E_{lm} with equalization tank hold-up, V_p , is illustrated in Fig 3.3.

When the penalty error for the tank volume limits was incorporated in the total error expression the resulting optimal tank outflow rate profile always gave an associated tank volume profile within the specified limits (V_{lu} and V_{lb}).

4.3 Penalty for Rate of Change of Tank Outflow Rate

A constraint is imposed on the rate of change of tank outflow rate for two reasons: (1) to ensure that the optimal tank outflow rate profile is "smooth", i.e. does not exhibit "spikes"; and (2) to avoid rapid changes in the tank outflow rate over a small range, which would have effects on downstream processes such as secondary

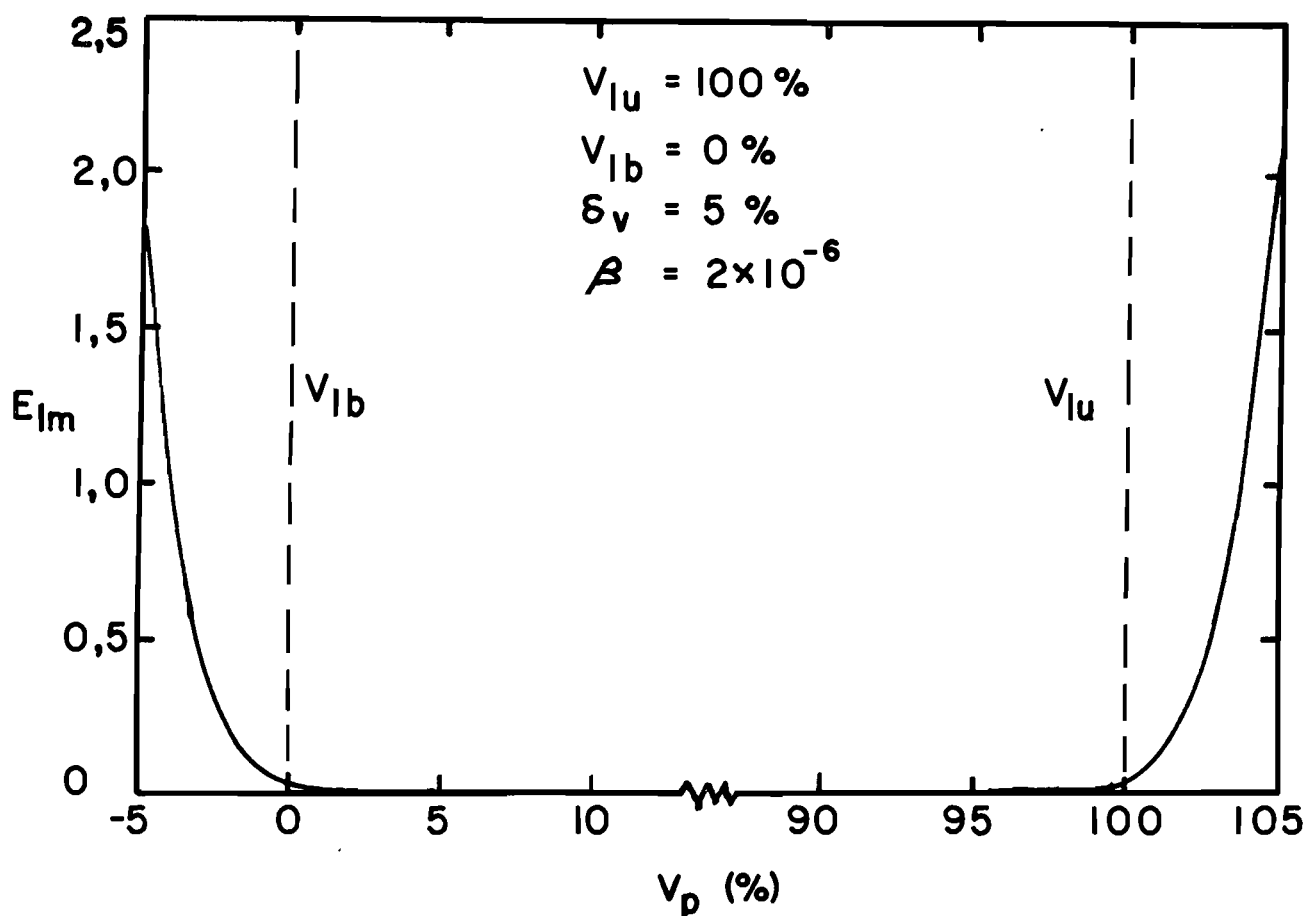


Fig 3.3 Variation of tank volume limit error, E_{lm} , with tank volume, V_p .

clarifiers, without being adequately reflected in the flow equalization error term integrated *over the whole day*.

In Section 4.2 it was shown that there must be a balance between the equalization error, integrated *over the day*, and the volumetric penalty error, given by the summation of the penalty errors at *points* where the volumetric limits are exceeded. Consider, for example, the case where the upper volume limit is exceeded at only one point in the profile, and this gives rise to a volumetric penalty error about equal in magnitude to the total equalization error, E_e , calculated over the *whole day*. By imposing a sharp change in outflow rate at that point in the profile the volumetric penalty error will decrease sharply, but will only result in a small increase in the equalization error integrated over the whole day; the nett effect

will be an appreciable decrease in the total equalization error. However, the outflow rate profile may then contain a near discontinuity at that point which is contrary to the objective to develop a "smooth" outflow rate profile. Hence, a constraint on the rate of change of outflow rate needs to be imposed so that excessively sharp changes can be avoided, and are spread out over a range about the point rather than being concentrated at the point.

In the day to day operation of an equalization facility, when the system is operating at or near its volume limits, particularly when insufficient inflow or hold-up is available, it is difficult to satisfy the mean flow and load requirements. If the optimization approach being discussed is utilised in the control strategy the equalization error will have the effect of forcing the outflow rate to the mean value as rapidly as possible when the volume becomes available. It is generally undesirable to transmit rapid flow rate changes to downstream units. These rapid changes must be damped by imposing a constraint on the rate of change of the outflow rate.

In order to avoid rapid changes in outflow rate a third error term is created which penalizes the rate of change of the outflow rate. The penalty error for the rate of change of the outflow rate is obtained by numerically integrating the absolute value of the slope of the outflow rate profile over the day, as follows:

$$E_s = \omega \sum_{i=1}^n |dF/dt| \quad (3.15)$$

where

E_s = penalty error for rate of change of tank outflow rate

ω = a weighting factor (constant)

Again a weighting factor, ω , is included in the expression so that the value of the penalty error, E_s , does not over-ride the effect of the equalization error, E_e . Guide-lines for the choice of the ω value are presented in Appendix B.

The total error term, therefore, is made up of three contributions:

- (i) An equalization error, E_e [Eq (3.12)]
 - (ii) A volumetric limit penalty error, E_{lm} [Eqs(3.13) and (3.14)]
 - (iii) A penalty error for the rate of change of tank outflow rate, E_s [Eq (3.15)]
- i.e.

$$E_t = E_e + E_{lm} + E_s \quad (3.16)$$

5. COMPUTER PROGRAM FOR EQUALIZATION ALGORITHM

The iterative optimization procedure utilized in the equalization algorithm for development of the optimal tank outflow rate profile was set out in Sections 3.1 to 3.4. Two optimization approaches were discussed, i.e. optimization by (1) the Method of Steepest Descent and (2) a Fast Convergence technique.

The procedures were developed over a period of time. As each procedure developed, modifications were incorporated in an ASCII FORTRAN computer program. This allowed evaluation of the equalization algorithm and the effect of different error expressions to be assessed, under various input flow and load patterns.

Initially the error expression consisted of only the *equalization error*, E_e , given by Eq (3.13). The equalization error was formulated so as to favour the development of an optimal tank outflow rate profile and associated effluent mass loading profile which did not exhibit sharp deviations from the mean. This was achieved by expressing the equalization error as a function of the square of the deviations. However, this expression, on its own, was found to be inadequate as the tank hold-up profile over the day sometimes exceeded the physical volume limits imposed by the selected tank size. This led to an additional term being included in the error expression, i.e. a *penalty error for the volumetric limits*, E_{lm} . The penalty error allowed upper and lower hold-up limits, V_{lu} and V_{lb} , respectively (specified as a percentage of the total tank volume), to be selected. However, problems were encountered, particularly with small tank sizes, in that there was "spikyness" in the optimal tank outflow rate

profile, although the volume constraints were obeyed. For this reason a third term was included in the error expression, i.e. a *constraint on the rate of change of tank outflow rate*. This constraint was based on the absolute value of the slope of the outflow rate curve, integrated over the day. This ensured the development of a "smooth" tank outflow rate profile, and also penalized rapid changes in the outflow rate that would adversely affect downstream processes:

The resulting equalization algorithm and error expressions were then accepted for further development because, for various forms of the input flow and load patterns, the response exhibited:

- (1) Stable convergence to the optimal tank outflow rate profile, and
- (2) A relatively "smooth" outflow rate profile, and an associated tank hold-up profile which did not exceed the specified tank volume limits.

It is possible that situations may arise where a particular selected influent flow and mass loading pattern does not cause requirements (1) and (2), above, to be met. In such cases it will be necessary to adjust the weighting factors α , β and w in the error expression. Guide-lines for adjusting the values of these weighting factors are given in Appendix B.

A flow chart for the generalized calculation procedure is shown in Fig 3.4(a), (b) and (c). More detailed flow charts for the sub-routines NEWPCV and ERCALC that are utilized to make an adjustment to an existing tank outflow rate profile and to calculate the value of the error expression, respectively, are shown in Figs 3(d) and (e).

Appendix B also presents detailed instructions for the use of the computer program, and a listing of the program. The program uses 49 half-hourly point values of the influent flow rate and concentration over the day, together with the process information (configuration, tank size, etc.). To develop the optimal equalization outflow rate profile the program utilizes either one of the two optimization approaches discussed in Section 3.3.

For purposes of comparison and graphical evaluation of the results obtained from application of the equalization algorithm, two separate plotting programs utilizing the CALCOMP package were written; one for "in-line" equalization, and another for "side-line" equalization. Listings of these programs, and detailed instructions for their use are also presented in Appendix B.

6. EFFECT OF WEIGHTING FACTORS IN THE ERROR EXPRESSION

The effect of the equalization configuration, mode of operation and tank size on the optimal outflow rate and mass loading profiles, under various fixed diurnal influent flow and load patterns, will be discussed in detail in Chapter 4. In this Section the effect of changes in the error expression weighting factors will be discussed. For this purpose one particular situation, where the configuration, tank size and influent flow and load patterns are specified, will be used, as follows:

An "in-line" equalization configuration is selected, where all the influent passes via the equalization tank to the downstream process. The size of the equalization tank may be specified in terms of the tank hydraulic retention time, or tank hold-up, based on the average inflow to the process, viz;

$$R_T = V_T / \bar{Q} \quad (3.17)$$

where

R_T = hydraulic retention time

V_T = volume of equalization basin

\bar{Q} = average influent flow rate.

In this example a tank hold-up of 5,5 hours is chosen, which means that at the average inflow rate, it will take 5,5 hours to fill the tank from empty. The tank volume is, therefore, 23 per cent of the daily inflow; this corresponds closely with the size of tank encountered in practice.

The upper and lower allowable tank volume limits are specified as 100 and 0 per cent of the total tank volume, respectively.

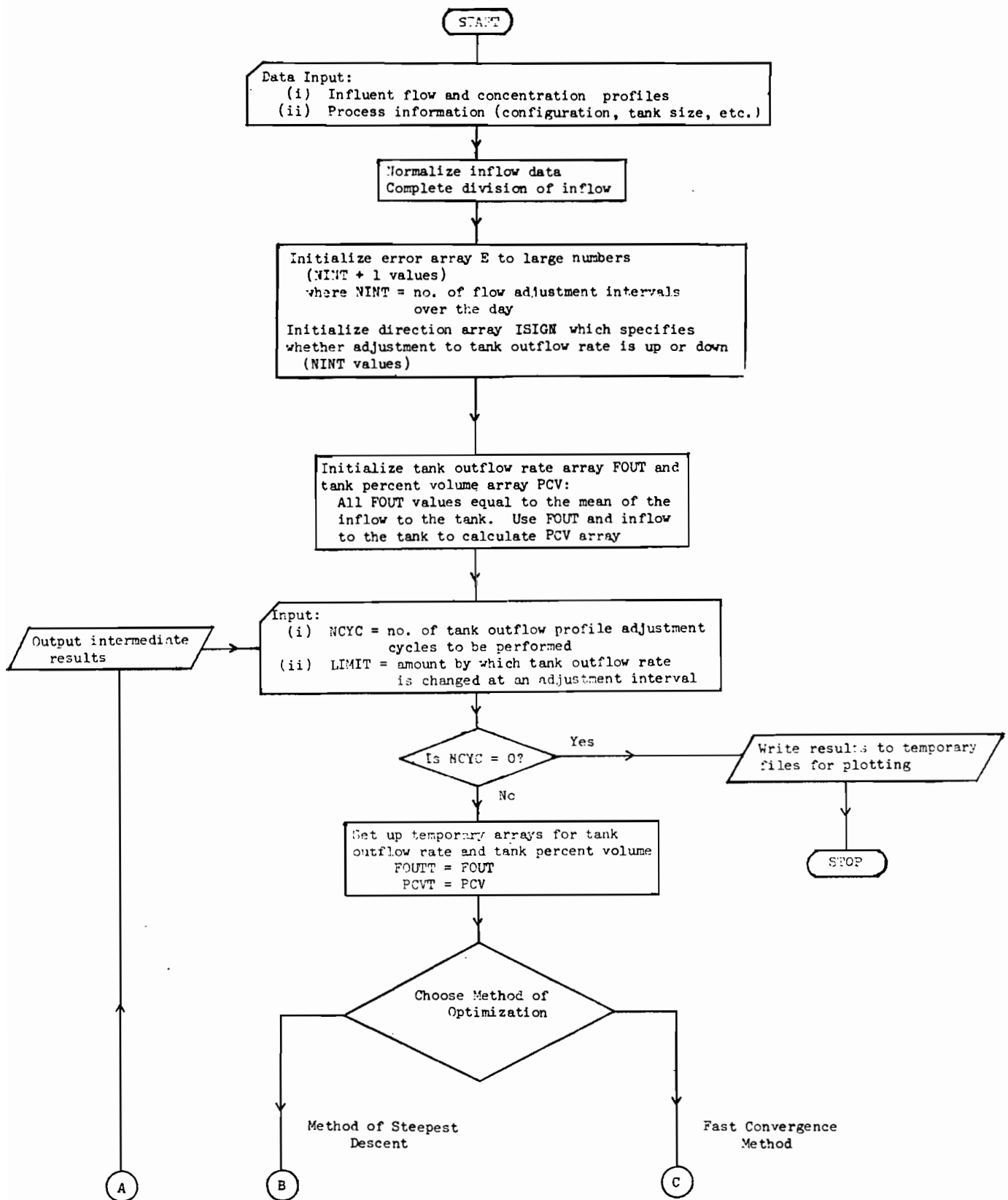


Fig. 3.4(a) Flow chart for the equalization algorithm showing the initialization of the general calculation procedure and selection of the method of optimization.

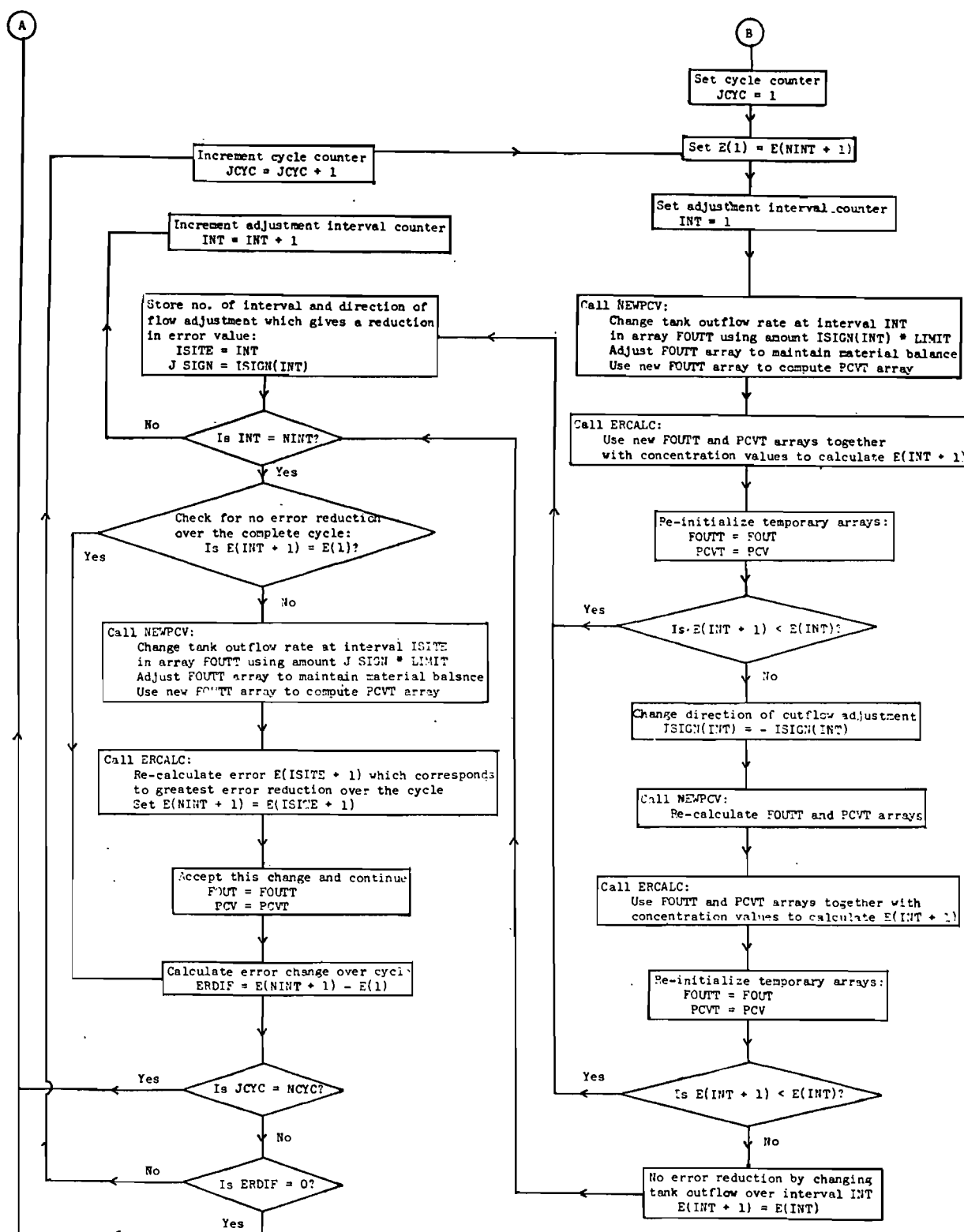


Fig. 3.4(b) Flow chart for the calculation procedure utilized with optimization by the Method of Steepest Descent.

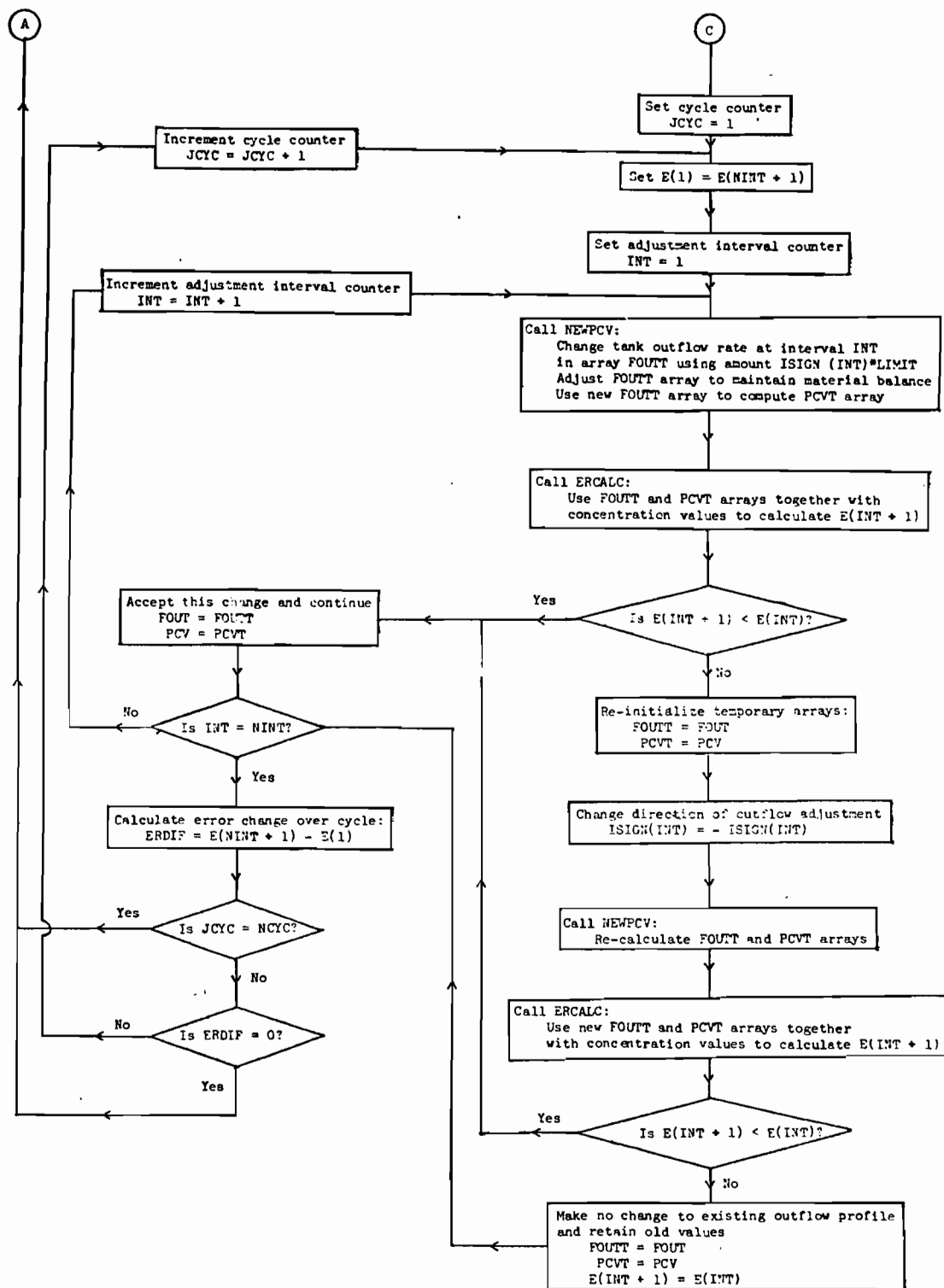


Fig. 3.4(c) Flow chart for the calculation procedure utilized with optimization by the Fast Convergence Method.

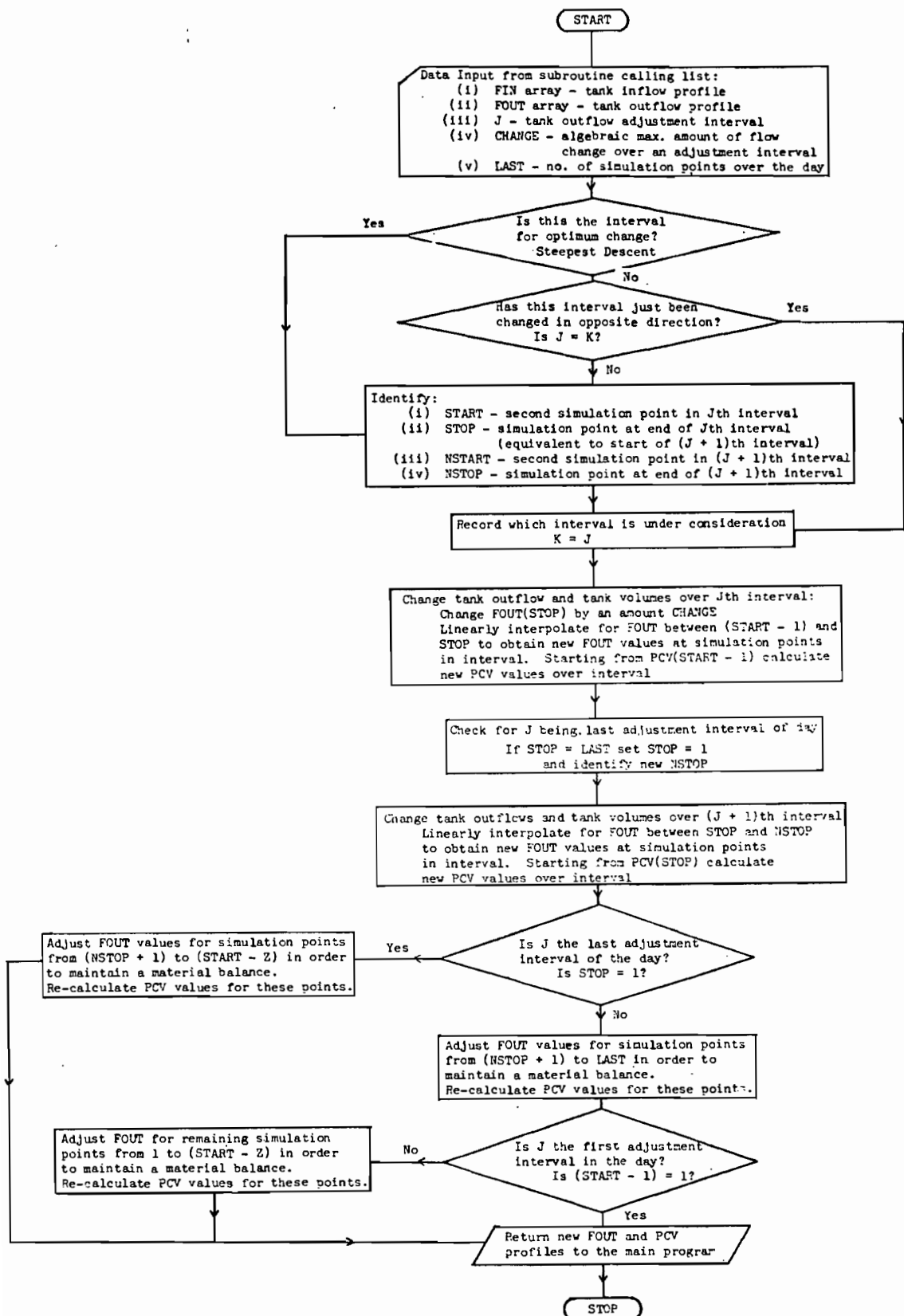


Fig. 3.4(d) Flow chart for the calculation procedure utilized in subroutine NEWPCV, where an adjustment is made to an existing tank outflow rate profile.

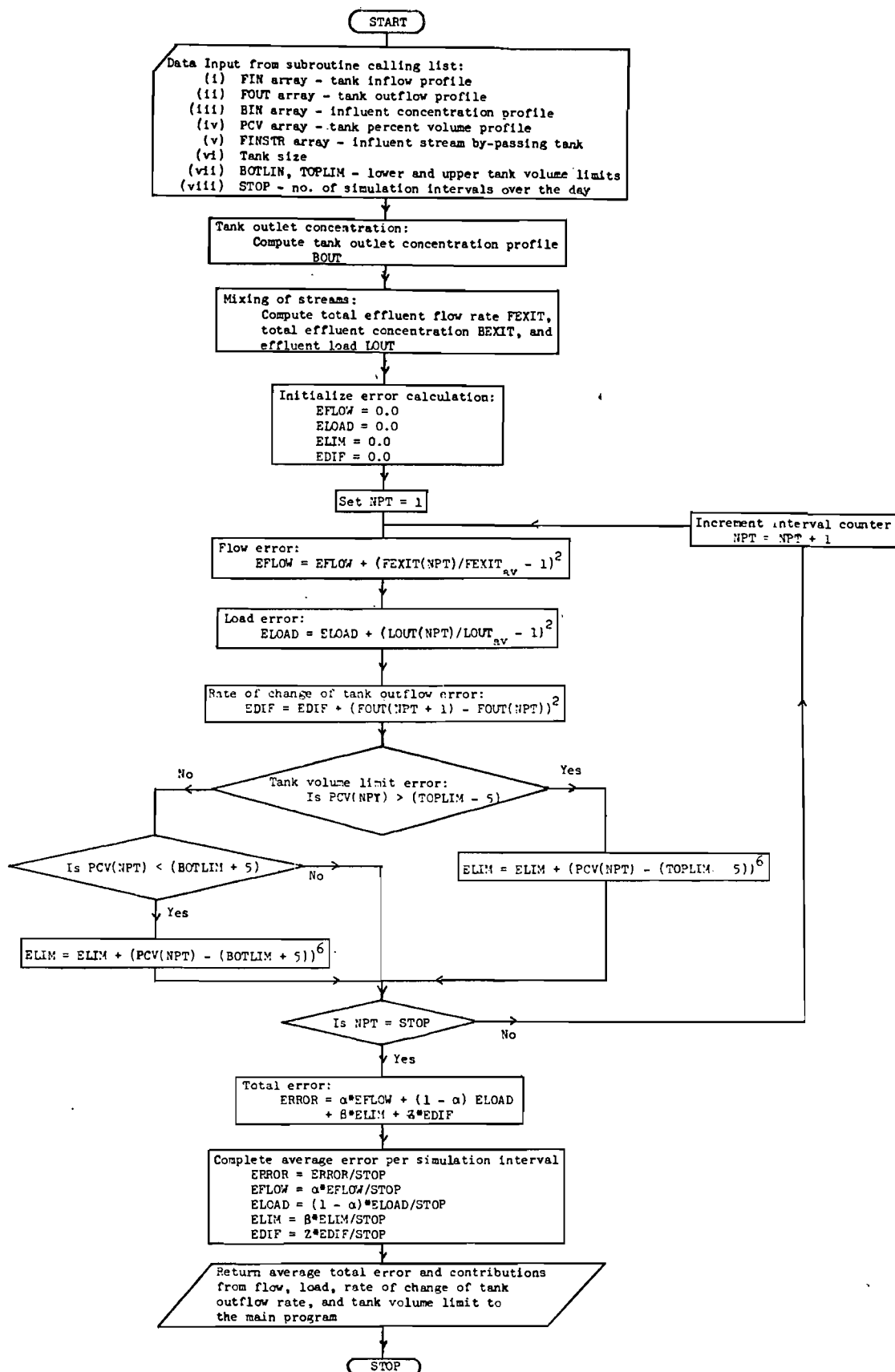


Fig. 3.4(e) Flow chart for the calculation procedure utilized in subroutine ERCALC, where the value of the error expression is calculated.

The influent flow rate and mass loading information is taken from data collected at the Cape Flats Sewage Works, Cape Town. For the period from Monday to Friday point values of the flow and concentration at half-hourly intervals over each day are used to obtain average point values over the day. "Smoothed" curves are then drawn through the averaged data points and 49 half-hourly point values of flow rate and concentration, and hence load, are obtained.

The weighting factors, α , β and w in the error expression are assigned values of 0,5, $2,0 \times 10^{-6}$ and 50,0 respectively.

The computer program for the equalization algorithm was used to develop the optimal tank outflow rate profile; the resulting profile and the associated tank hold-up profile together with the effluent mass loading profile are presented in Fig 3.5. The influent flow and load profiles are also shown in the Figure, and provide a background for assessing the effectiveness of the equalization procedure.

From Fig 3.5 certain features regarding the nature of the equalization profiles are evident:

- (1) It is clear that the equalization tank is very effective in reducing variations in the flow rate about the mean.
- (2) The reduction of variations in the mass loading profile, although substantial, is not as large as that for the flow rate profile. However, it is important to note that the principal deviation from the mean is a *decrease*, and this decrease occurs over a relatively short range. The peak load is effectively smoothed to near the mean value; hence, the effluent load profile will still cause a substantial reduction in the peak oxygenation capacity required in the plant.
- (3) It is evident that, although the lower allowable tank hold-up limit is 0 per cent of the tank volume, the tank is not emptied; there is a minimum hold-up of about 10 per cent of the tank volume. This minimum hold-up allows some damping of influent concentration variations and thus contributes to the load equalization.
- (4) The principal deviation in load occurs at about 12h00 where

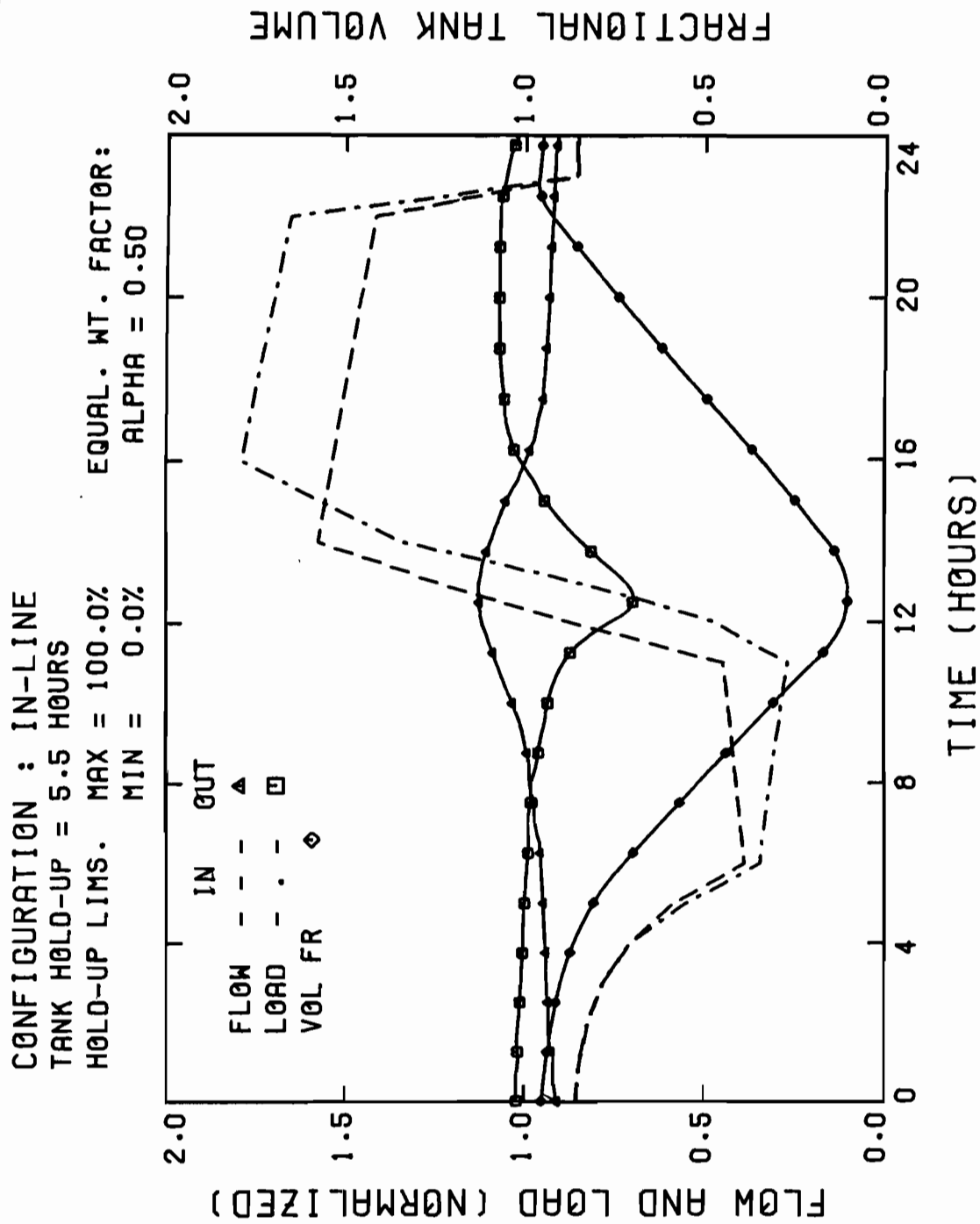


Fig. 3.5 Optimal tank outflow rate profile and associated tank hold-up profile and effluent mass loading profile for a 5,5 hour "in-line" equalization tank under fixed diurnal input patterns of flow rate and load (Cape Flats data), where $\alpha = 0,5$.

(a) the influent flow and load have just passed their minimum values, and (b) the tank hold-up is small. The solution procedure counters the extent of the plunge in the load profile by slightly increasing the tank outflow rate. The increase in outflow rate, however, is limited by two factors:

- (a) The low inflow rate and the small hold-up volume available; increasing the outflow rate will decrease the minimum hold-up volume, thereby diminishing the effect of concentration damping which enhances load equalization.
- (b) The constraint on the rate of change of the outflow rate.

It is clear that this time of minimum inflow and minimum volume is the most critical part of the control cycle.

- (5) There is a second feature responsible for the greater efficiency of flow equalization as opposed to load equalization. In the example the equalization weighting factor, α , has been assigned a value of 0.5, giving equal prominence to the flow and the load error terms in the equalization error, E_e [Eq (3.10)]. However, as the load is calculated from the product of flow and concentration, flow receives additional prominence through the load parameter.
- (6) Features apparent from the hold-up profile are that:
 - (a) When the tank is filling, influent flow rate exceeds outflow rate;
 - (b) When the tank is emptying, outflow rate exceeds influent flow rate; and
 - (c) When there is a change from emptying to filling, or *vice versa*, i.e. $dV/dt = 0$, the outflow rate equals the influent flow rate. See Fig 3.5.

The example presented above serves as a basis for comparison of the effects when the values of the weighting factors in the error expression are changed.

6.1 Effect of Equalization Error Weighting Factor, α

By increasing the value of α relatively more weight is accorded to

flow equalization relative to load equalization, and *vice versa*. Where settling tanks are under-designed and solids discharge is a problem, flow equalization might be of greater importance than load equalization. On the other hand, in plants designed for nitrification-denitrification and phosphorus removal, it may be more important to equalize the load. Hence the value of α will in practice be chosen on the basis of how critical the flow or the load variations are on the desired behaviour for a particular installation.

In the example above α was assigned a value of 0,5. The effect of changing α is illustrated by repeating the example, but with the value of α decreased from 0,5 to 0,1, i.e. more weight is given to load equalization relative to flow equalization. The resulting optimal solution is shown in Fig 3.6. A comparison of Figs 3.5 and 3.6 shows that there is an appreciable improvement in the equalization of the load, particularly over the critical region at about 12h00.

The principal contribution to the enhanced load equalization occurs at the expense of an increased outflow rate over the critical period. The interdependence of flow and load leads to the anomalous requirement that, when the tank hold-up is approaching zero, in order to maintain an equalized load the outflow rate must be increased, thereby increasing the rate at which the tank will empty.

6.2 Effect of Changing Tank Volumetric Limit Penalty Error Weighting Factor, β

The function of the penalty error for volumetric limits, E_{lm} [Eqs (3.13) and (3.14)], with its associated weighting factor, β , is to ensure the development of an outflow rate profile that results in a hold-up profile that does not exceed the specified upper and lower hold-up limits. Provided the penalty error serves this function, it was observed that it is not really necessary to consider the effect of varying the value of β as the parameter has only a minor effect on the optimal tank outflow rate and load profiles; once the hold-up profile does not exceed the specified limits the effect of the penalty error is insignificant.

6.3 Effect of Weighting Factor for Rate of Change of Outflow Rate, ω

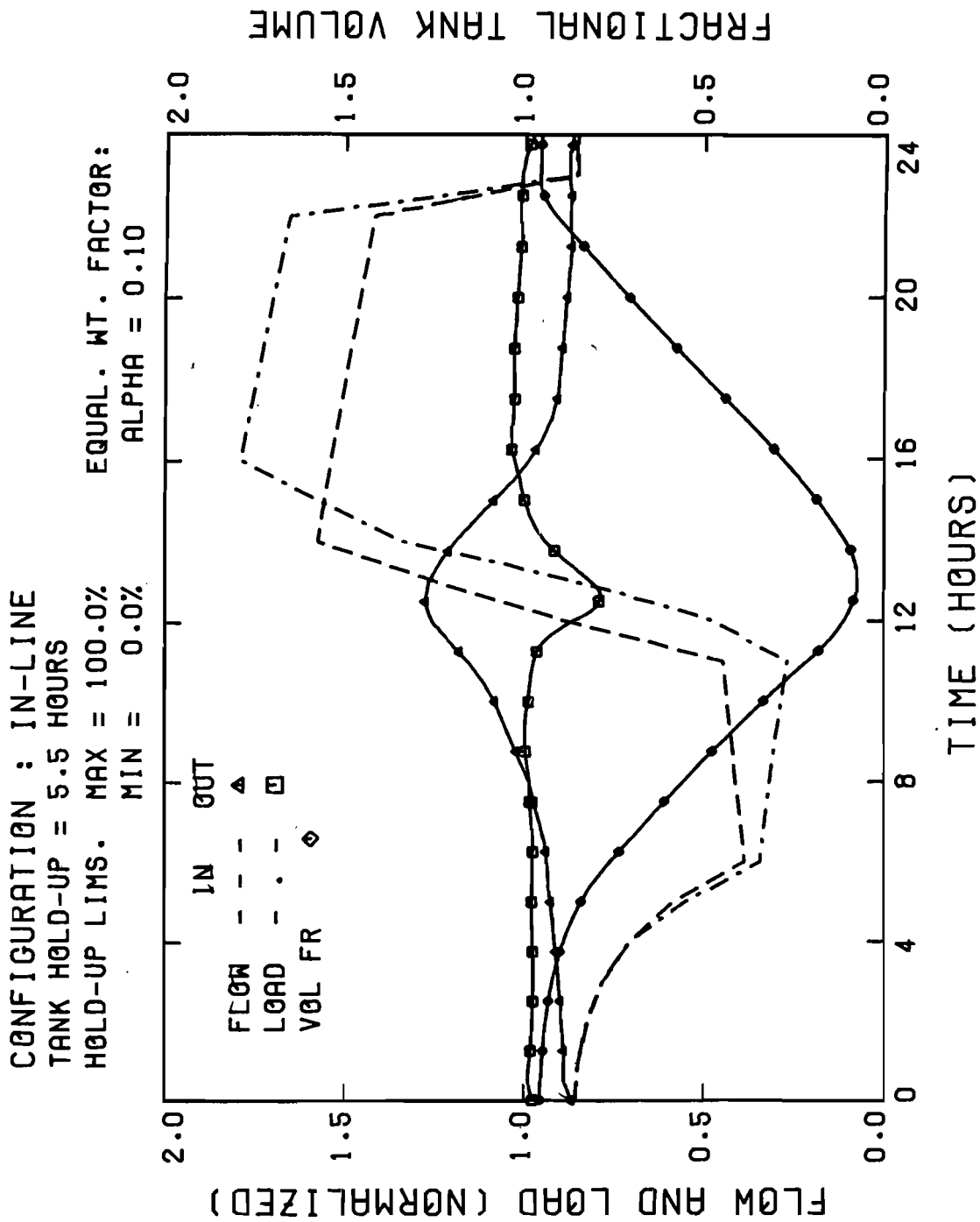


Fig. 3.6 Optimal equalization results illustrating the effect of the equalization error weighting factor, α , with $\alpha = 0, 1$ (cf Fig. 3.5 where $\alpha = 0, 5$).

The function of imposing a constraint on the rate of change of outflow rate is (a) to ensure the development of a "smooth" outflow profile which is free from spikes induced by the mathematical procedure, and (b) to constrain the rate of change of outflow rate which would adversely affect downstream processes. In essence the effect of increasing ω is to increase the importance of flow equalization. This effect is illustrated by repeating the example of Section 4, with the difference that the value of ω is increased from 50,0 to 200,0. The optimal results are presented in Fig 3.7.

It is apparent that the optimal tank outflow rate profile exhibits smaller deviations from the mean, i.e. better flow equalization, at the expense of the load profile. Although the effect is relatively small, it is desirable that a small value of ω , which still serves the required function, is selected. This will ensure that the function of the equalization weighting factor, α , is not clouded by artificially according more importance to flow equalization relative to load equalization.

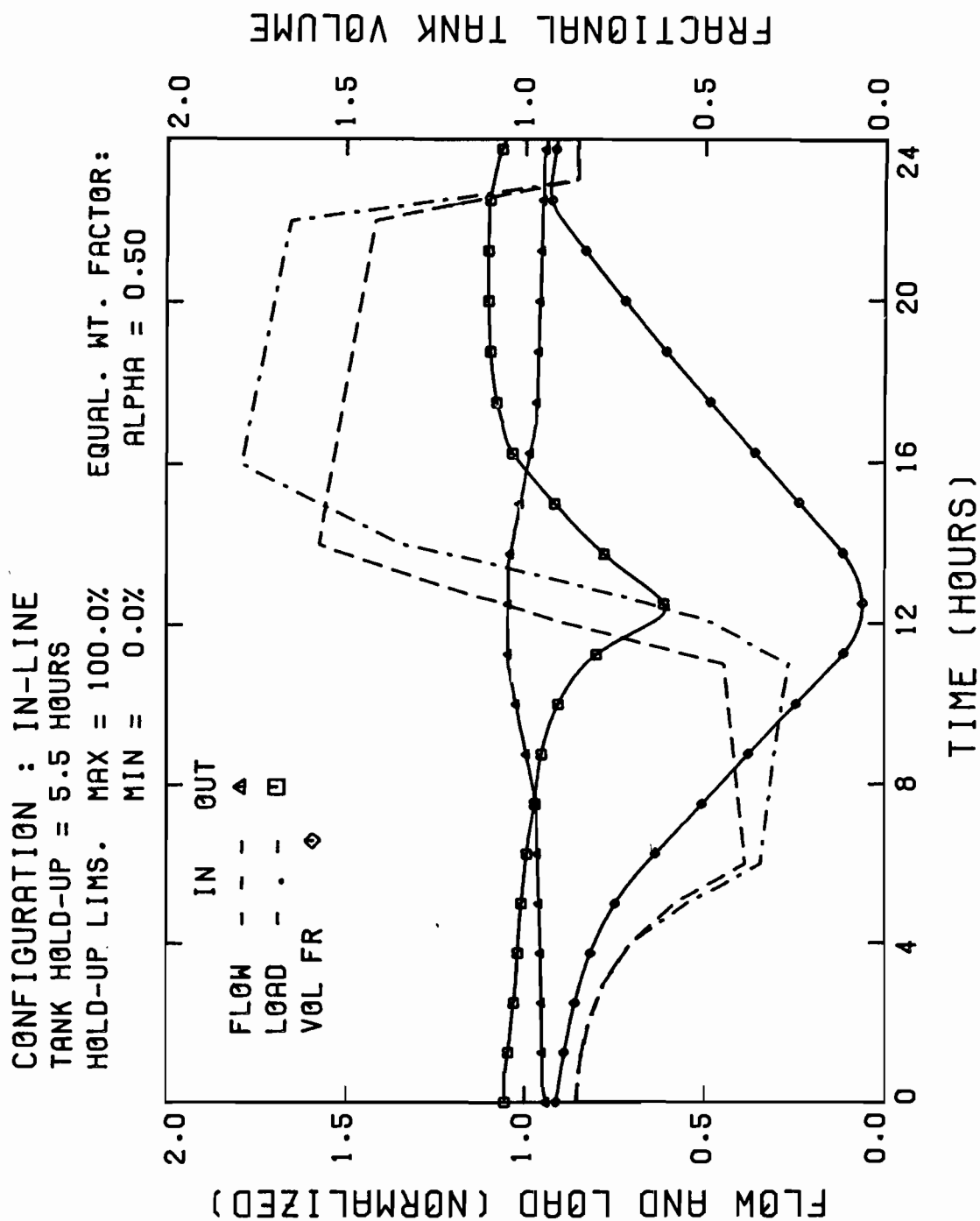


Fig. 3.7 Optimal equalization results illustrating the effect of the weighting factor for the constraint on the rate of change of tank outflow rate, ω , with $\omega = 200$ (cf Fig. 3.5 where $\omega = 50$).

CHAPTER FOUR

APPLICATION OF THE EQUALIZATION ALGORITHM UNDER INVARIANT DAILY INFLUENT FLOW AND LOAD PATTERNS

1. INTRODUCTION

The objective of the equalization algorithm is to minimize the deviations over the day of both the tank outflow rate and effluent load rate from their respective mean values subject to a number of constraints. If the influent flow rate and load do not have identical patterns then, for the size of equalization tank normally encountered in practice, it will not be possible to obtain complete equalization of both flow and load simultaneously. (This has been demonstrated in Chapter 3). In such cases this poses the question: What degree of equalization can be achieved? To answer this question it is necessary to develop a measure or measures to compare the deviations of flow and load before and after equalization. Such measures are also important for another reason - they will allow evaluation of the effects that changes in certain physical parameters such as input patterns, operational methods, etc. have on the degree of equalization. Information of this kind will give guidance as to the design of the most efficient system in a given situation.

1.1 Measures of the Effectiveness of Equalization

There are two possible approaches to assessing the effectiveness of equalization; the first is qualitative (visual) and the second is quantitative (numerical).

- (1) Qualitative assessment. The graphical output of results, examples of which are shown in Chapter 3, allows a visual comparison of the input with the output flow and load profiles. Where a parameter is changed in value (for example, tank retention time), by comparing the outputs under the *same* inputs of flow and load, a visual assessment can be made of the effects of the change in value of the parameter.

Visual comparison can be most persuasive and dramatic in bringing out the improvements in flow rate and load achieved by equalization. Besides highlighting the equalization action it also shows up the qualitative changes in the *pattern* of the effluent profiles which, in turn, may influence the design of the plant. For example, in Fig 3.5, Chapter 3, the influent load pattern shows an extended *peak* in the cycle; in the effluent pattern the peak is converted to a virtually constant value with a sharp *trough* of relatively short duration. The latter profile will be much more favourable for simple D.O. control procedures than the former while, in addition, the peak aeration requirements may be seen to be markedly reduced.

Visual assessment alone, however, does not provide a quantitative guide as to the degree of improvement achieved or allow quantitative evaluation of the equalization as a specified parameter is changed incrementally. Visual assessment must be augmented, therefore, by some quantitative measure of the effectiveness of equalization.

- (2) Quantitative assessment. A numerical measure of the effectiveness of equalization can be obtained if (1) an "influent equalization error", $(E_e)_i$, is calculated for the deviations of the influent flow and load profiles from their respective mean values on the same basis as for the outflow profiles, $(E_e)_o$, and (2) a ratio is formed of the output to input error. This ratio is defined as the *relative error*, viz,

$$E_r = (E_e)_o / (E_e)_i \quad (4.1)$$

where

$(E_e)_o$ = equalization error for outflow rate and effluent mass loading profiles [Eq (3.11)]

$(E_e)_i$ = equalization error for influent flow and mass loading profiles [Eq (3.11)].

In Eq (4.1) the values of E_e reflect only the non-ideality of flow and load equalization; the values do not include the penalty

error components [see Eq (3.16)]*. By considering only the equalization error portion ensures that a true measure of equalization effectiveness is achieved.

1.2 Preliminary Considerations

Before discussing the influence of the various parameters that affect equalization efficiency certain factors that have a bearing on the results obtained from application of the equalization algorithm should be considered. These are:

(1) Selection of Influent Flow and Load Patterns. From Section 1, Chapter 2, two features are apparent regarding the form of the diurnal influent flow and load patterns to a WWTP:

- The form of the average diurnal influent patterns is different between weekdays and weekend days.
- The form of these patterns changes from season to season.

Because of the changes in the form of the mean diurnal influent patterns there is a flexibility in the choice of the influent pattern to be used for testing purposes. For example, different profiles will be obtained if, in one case, the influent pattern is obtained by averaging results over every day for a certain period, and in another case, by averaging results only over the weekdays in that period. However, the reason for applying the equalization algorithm is to evaluate the effectiveness of an equalization facility; clearly the influent flow and load patterns chosen should be those that provide the most stringent test of the process. Under normal conditions this generally corresponds to the case where the influent flow and load profile is obtained from the mean *weekday* influent pattern because then both (1) the mean daily influent flow rate, and (2) the variations in the influent flow and load about their respective mean values are a maximum. As shall be shown later, in any selected configuration, as the mean flow and load and the variations about the mean increase, so the degree of equalization declines.

* In the case of the *effluent* patterns, as optimality is approached (through utilizing the equalization algorithm) the penalty errors in any case reduce to relative insignificance so that the total error, E_t , virtually equals E_e at the optimum solution.

In this investigation the influent flow and load patterns were obtained by first taking average point values of the flow and load at half-hourly intervals over the day, and then drawing "smoothed" curves through the averaged data points. In practice the data on flow and load will not be smooth; relatively small random variations of short duration will be superimposed on the average trend pattern of both flow and load. In flow-through equalization these variations generally are of little importance as they will be attenuated by the damping effect inherent with equalization because (1) a "smooth" outflow is withdrawn from the tank, and (2) it is assumed that the tank contents are well mixed. However, the existence of these short term variations is of importance in "side-line" equalization where not all the influent flow passes via the equalization tank; this feature is discussed when the suitability of "in-line", as opposed to "side-line" equalization, is considered.

(2) Different Influent Patterns. In evaluation of the equalization algorithm the effect of different influent patterns on the efficiency of equalization needs to be considered. For this reason data was collected at two full-scale wastewater treatment plants; the Cape Flats Sewage Works, Cape Town, and the Goudkoppies Sewage Works, Johannesburg, as the influent profiles of these plants differ significantly (see Section 2.2, Chapter 2).

(3) Weighting Factors and Volume Limits. For comparison purposes a fixed set of weighting factors (α , β and ω) and equalization tank volume limits will be used, as listed in Table 4.1.

Weighting Factors: Equal weight is assigned to flow and to load ($\alpha = 0,5$) for no reason other than that this is perhaps the most likely selection that will be made. The values of β and ω were selected from experience to provide stable operation of the algorithm while yet ensuring that the function of these penalty errors was served.

Volume Limits: Tank upper and lower volume limits of 100 and 0 per cent, respectively, were selected even though these are not likely to be used in practice. However, these extreme values allow a direct comparison to be made between results from tanks

of different sizes which is not possible once the volume limits differ from 0 and 100 per cent.

- (4) Description of Tank Size. Equalization tank volumes are specified in terms of the tank hydraulic retention time, based on the average influent flow rate [Eq (3.17)]. It should be noted that, *in cases where not all the flow passes through the tank ("side-line" equalization), the specified tank retention time will also be based on the total inflow to the equalization installation, not on the inflow to the equalization tank only.*

2. FACTORS INFLUENCING EQUALIZATION EFFICIENCY IN IN-LINE EQUALIZATION

2.1 Size of Equalization Tank

To investigate the effect of the equalization tank size on the efficiency of equalization influent patterns from the Cape Flats outfall were used. The equalization response was obtained by applying the equalization algorithm (for the development of the optimal tank outflow rate profile) to an *in-line* equalization tank with retention times of 3, 4, 5 and 6 hours; the results are shown in Figs 4.1, 4.2, 4.3 and 4.4, respectively. Each Figure shows the effluent flow and load rates and the associated tank volume response over the course of the day, as well as the influent flow and mass loading patterns, for purposes of comparison.

Table 4.1 Error Expression Weighting Factors and Physical Volume Constraints Used in Simulations

Symbol	Description	Value
α	Weighting factor for equalization error	0,5
β	Weighting factor for tank volume limit penalty error	$2 \cdot 10^{-6}$
ω	Weighting factor for rate of change of tank outflow rate penalty error	50,0
V_{lu}	Allowable upper limit of tank hold-up	100%
V_{lb}	Allowable lower limit of tank hold-up	0%

Qualitatively a visual comparison of the influence of the tank size on equalization indicates three important features. (A number of features regarding the response obtained from application of the equalization algorithm have been discussed in Section 6, Chapter 3, and are not repeated here):

- (1) As the equalization tank retention time increases, the flow and load variations both decrease.
- (2) At short retention times the effluent flow and load rate profiles tend to assume the character of the influent profiles. Conversely, at long retention times the effluent profiles both become relatively independent of the influent profiles.
- (3) Improvement in equalization efficiency with increasing tank size is not linear. Visually, there is a greater improvement in both flow and load equalization from a 3 to a 4 hour than from a 5 to a 6 hour tank retention time.

Quantitatively the relationship between the equalization efficiency and the size of the equalization tank may be delineated by plotting the relative error, E_r , versus the equalization tank retention time, as shown in Fig 4.5:

- (1) The relative error decreases almost linearly with increasing tank size, to a tank retention time of about 3,5 hours. For longer retention times the relative error decreases more gradually, and flattens out to an almost constant value above a retention time of about 7 hours.
- (2) Increasing the retention time up to about 4 hours produces substantial improvement in the equalization effectiveness, but,
- (3) Above a retention time of 6 hours the small improvement in equalization effectiveness probably would not justify the increased capital cost.
- (4) From an economic point of view the optimum practical retention time appears to be in the range of 4 to 6 hours.

2.2 Influent Flow and Load Patterns

The study in Section 2.1 was carried out using data from the Cape

CONFIGURATION : IN-LINE
 TANK HOLD-UP = 3.0 HOURS
 HOLD-UP LIMS. MAX = 100.0%
 MIN = 0.0%
 EQUAL. WT. FACTOR:
 ALPHA = 0.50

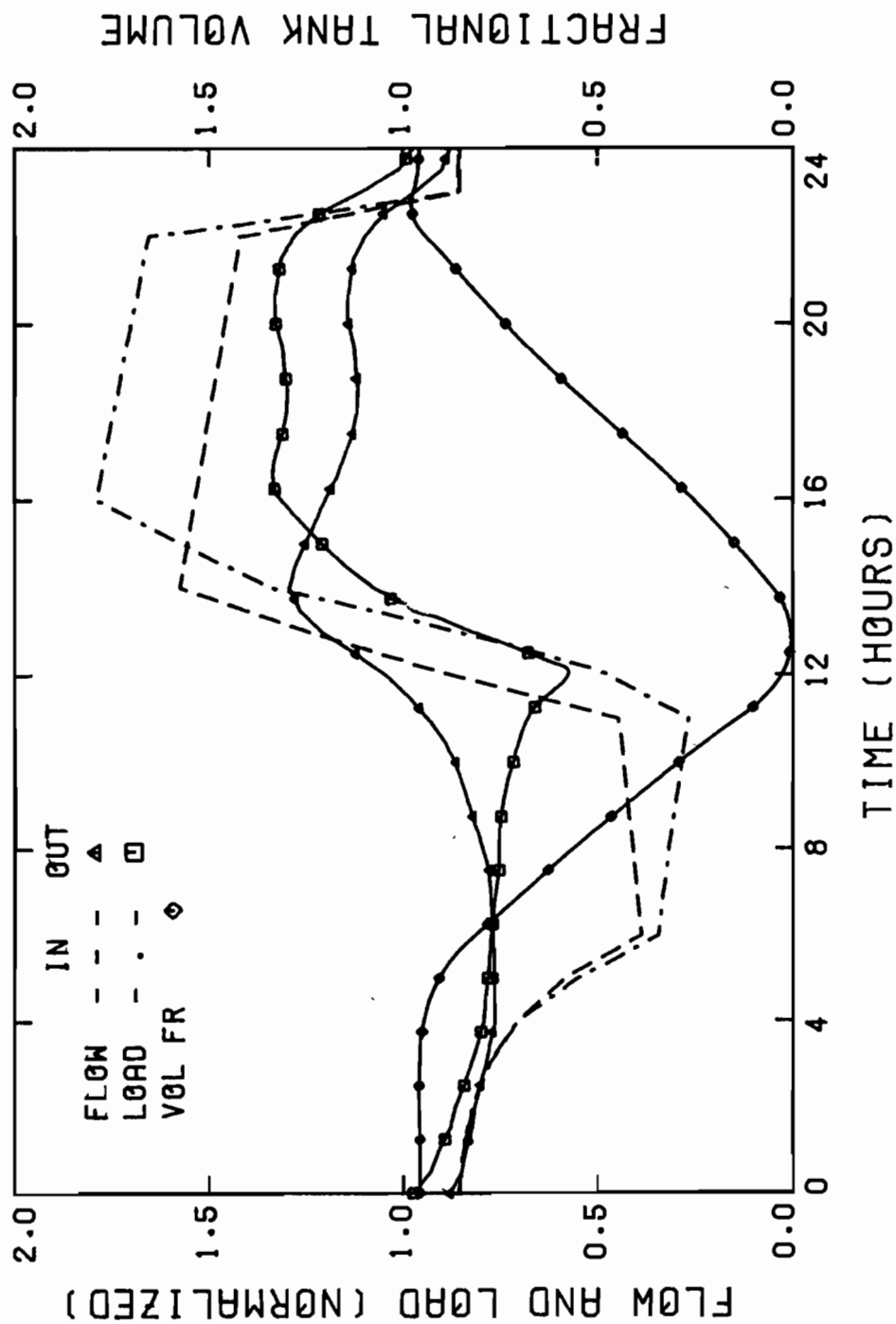


Fig. 4.1 Optimal tank outflow rate profile and associated tank hold-up profile and effluent mass loading profile for a 3 hour retention time "in-line" equalization tank under fixed diurnal input patterns of flow rate and load (Cape Flats data).

CONFIGURATION : IN-LINE
 TANK HOLD-UP = 4.0 HOURS
 HOLD-UP LIMS. MAX = 100.0%
 MIN = 0.0%
 EQUAL. WT. FACTOR:
 ALPHA = 0.50

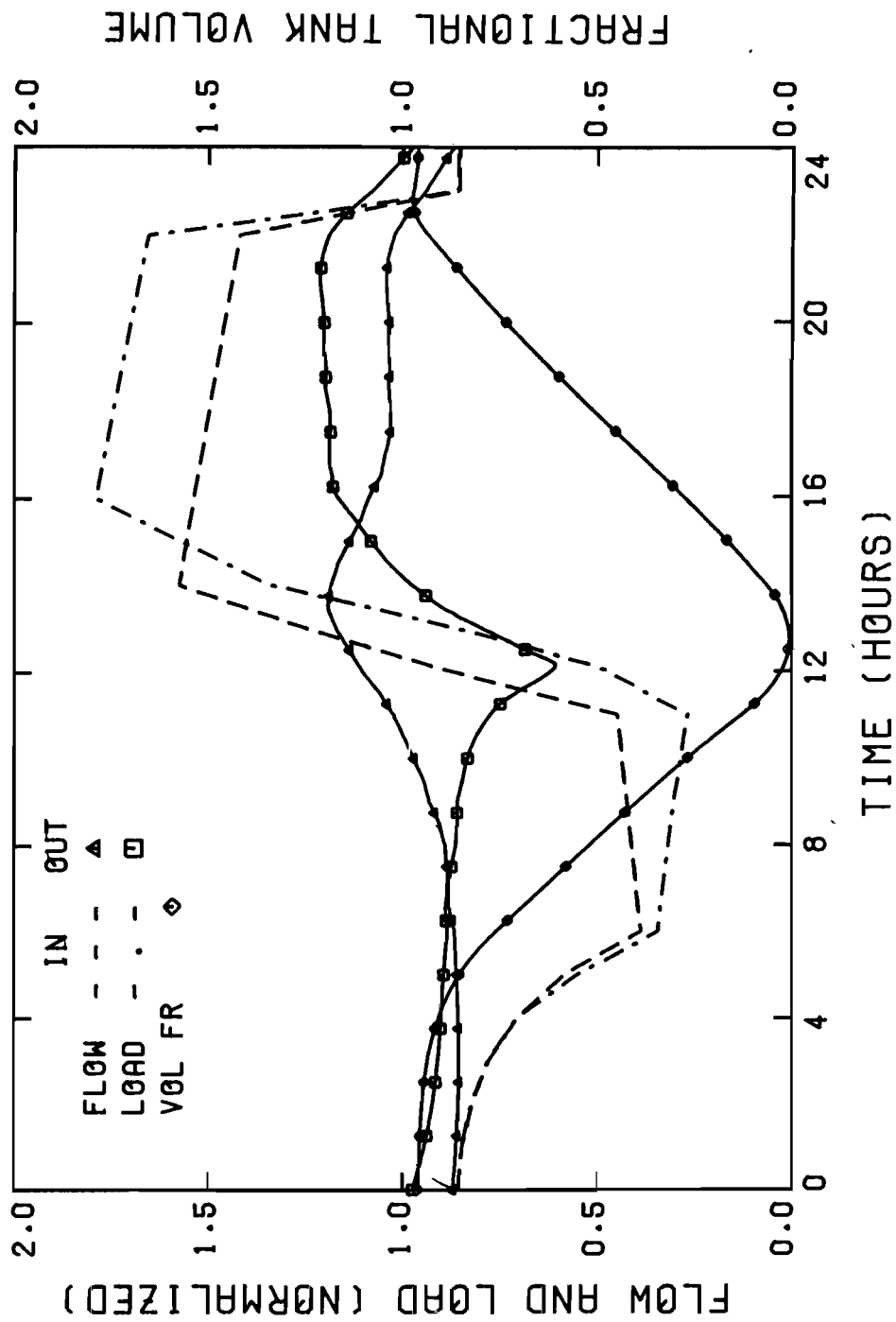


Fig. 4.2 Optimal tank outflow rate profile and associated tank hold-up profile and effluent mass loading profile for a 4 hour retention time "in-line" equalization tank under fixed diurnal input patterns of flow rate and load (Cape Flats data).

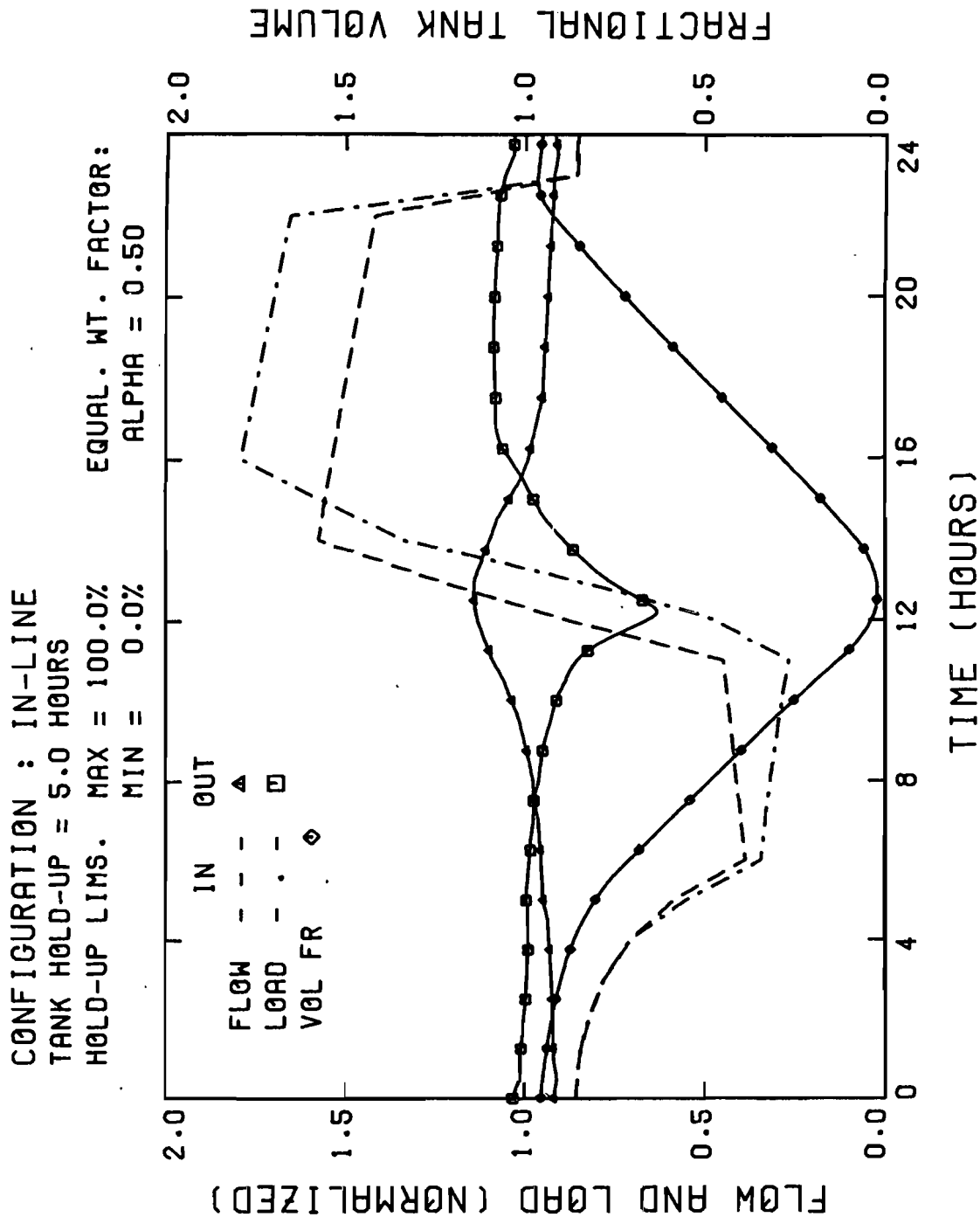


Fig. 4.3 Optimal tank outflow rate profile and associated tank hold-up profile and effluent mass loading profile for a 5 hour retention time "in-line" equalization tank under fixed diurnal input patterns of flow rate and load (Cape Flats data).

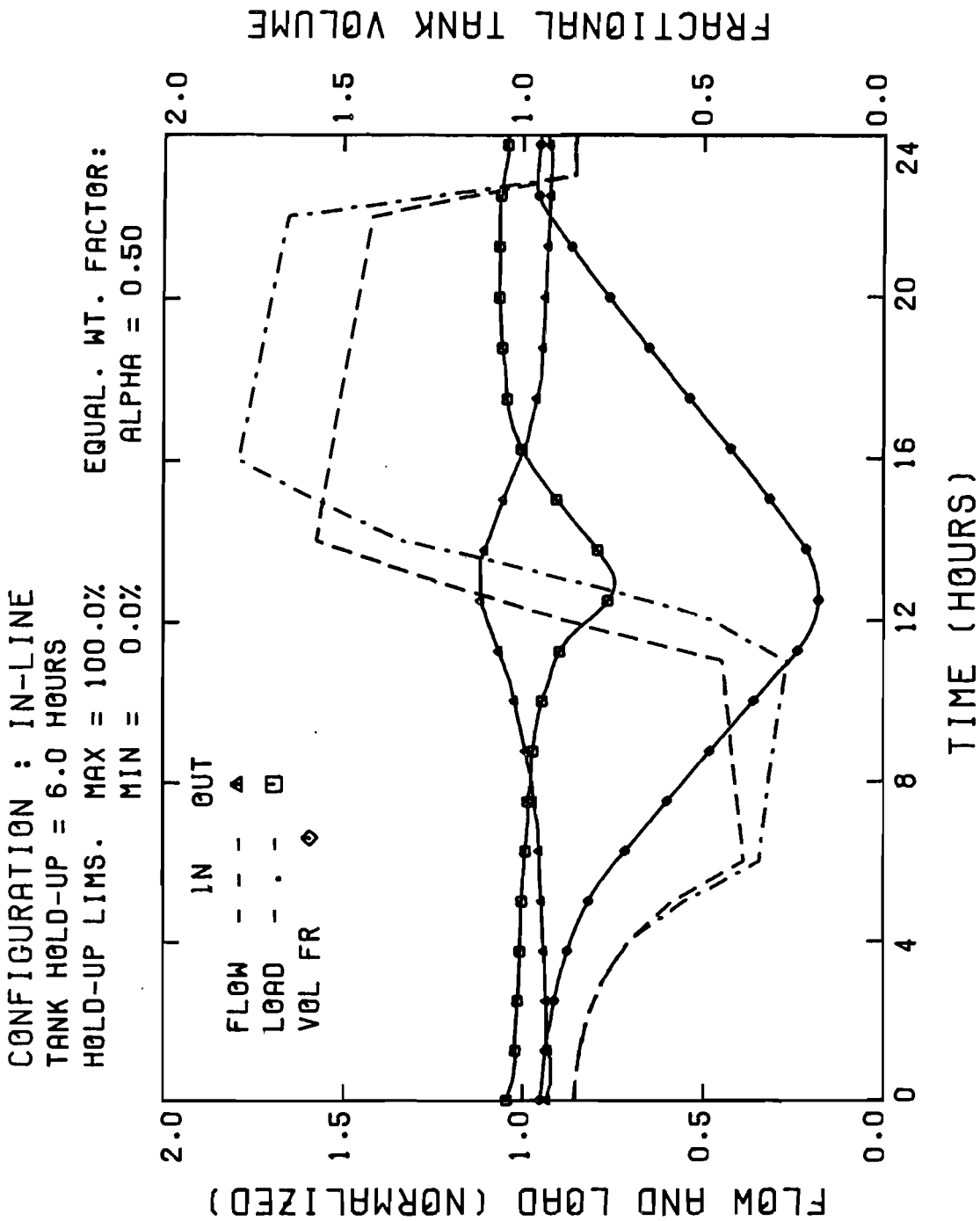


Fig. 4.4 Optimal tank outflow rate profile and associated tank hold-up profile and effluent mass loading profile for a 6 hour retention time "in-line" equalization tank under fixed diurnal input patterns of flow rate and load (Cape Flats data).

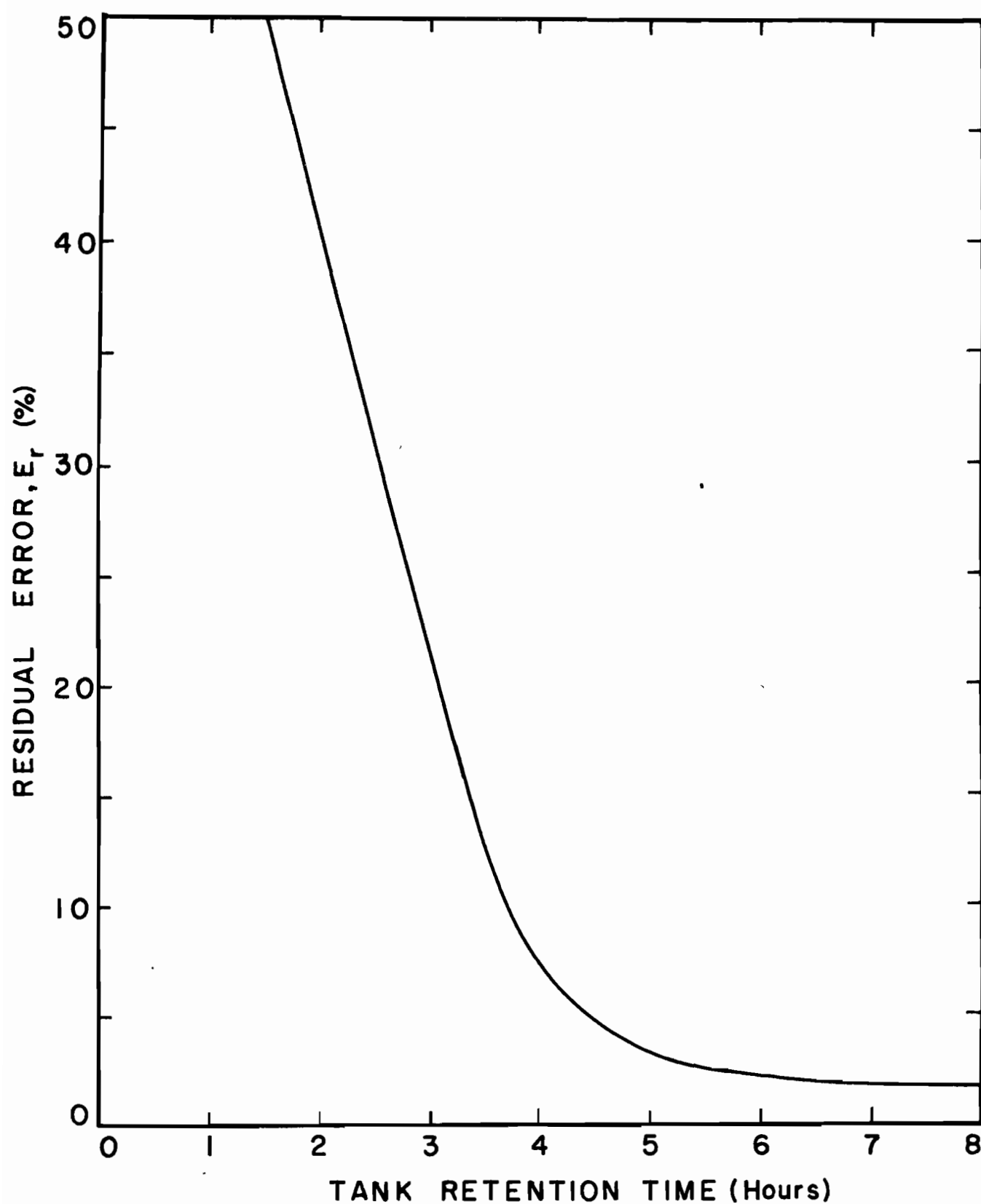


Fig. 4.5 Plot of relative error, E_r , (as a percentage) versus in-line equalization tank retention time (Cape Flats data).

Flats Sewage Works. For purposes of evaluating the effects of different influent flow rate and load patterns on equalization a second set of patterns was analyzed from data collected at the Goudkoppies Sewage Works. (The profiles were averaged from week-day data in the same manner as those for the Cape Flats WWTP, and are shown in Fig 4.6). The flow and load patterns for Goudkoppies indicate the following similarities and differences with those for the Cape Flats (Fig 4.1):

- (1) The flow rate and load patterns at both locations are similar in that the minima and maxima occur before and after midday.
- (2) The peak flow rate and peak load at Goudkoppies are sustained for a shorter period of time than at the Cape Flats.
- (3) The cyclic flow rate pattern is out of phase with the associated load pattern to a greater extent at Goudkoppies than at Cape Flats.

Optimum outflow patterns were determined for the Goudkoppies data using the equalization algorithm. The effects of the influent patterns for both WWTP's on their equalization efficiency is

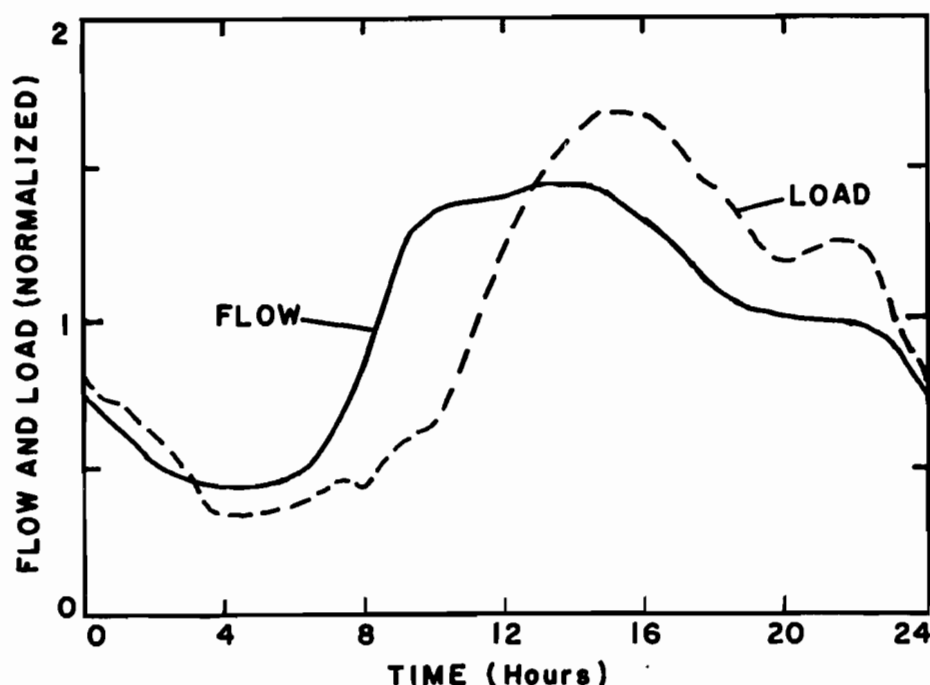


Fig 4.6 Influent flow and load patterns for Goudkoppies WWTP.

illustrated in Fig 4.7. For each set of influent patterns the relative error, E_r , is plotted versus the in-line equalization tank retention time. The form of the resulting curves, although similar, differ in the following aspects:

- (1) Up to a retention time of 3,5 hours the equalization tank at Goudkoppies provides better equalization than the Cape Flats.
- (2) The relative error, E_r , for Goudkoppies begins to flatten out at a lower retention time than for the Cape Flats.
- (3) The decrease of the relative error with increasing tank retention time is not as rapid for the Goudkoppies data as for the Cape Flats data.
- (4) The minimum relative error for the Cape Flats data is smaller than that for the Goudkoppies data.

The behaviour noted in (2), above, is because the peak flow rate and peak load are maintained for a shorter period in the Goudkoppies than

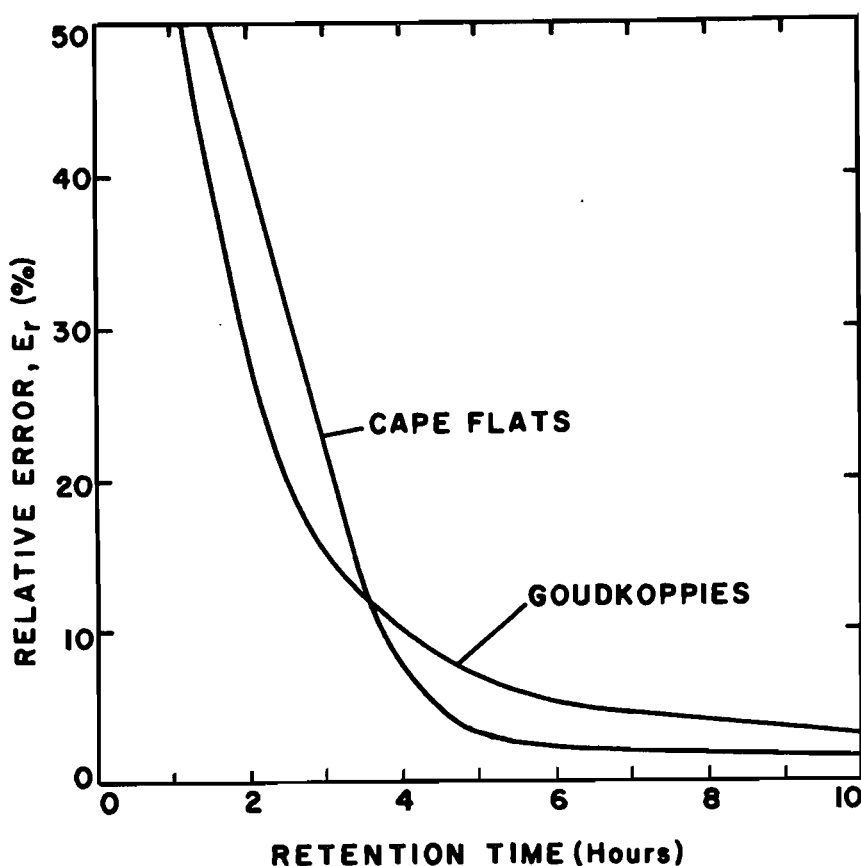


Fig 4.7 Effect of influent flow and load pattern on equalization efficiency.

in the Cape Flats influent patterns - in general, at short equalization tank retention times the equalizing efficiency is higher where the lengths of the periods of peak input are shorter.

With regard to (3) and (4), this behaviour appears to be due to the relatively large difference in phase between the influent flow rate and load patterns exhibited by the Goudkoppies influent patterns. From Fig 4.6 it is evident that, after passing through their respective minima, the Goudkoppies input flow rate equals the average daily flow rate 2,8 hours before the load attains the same condition, whereas for the Cape Flats influent patterns (Fig 4.1) the flow rate leads the load by only about 1 hour at that point in the cycle. To verify this conclusion a hypothesized case was considered where the phase difference was reduced by shifting the Goudkoppies influent flow rate data to occur 2 hours later; the resulting influent flow rate and load patterns are shown in Fig 4.8. From a comparison of Figs 4.6 and 4.8 it is apparent that there is a slight change in the form of the influent load pattern; this slight change is due to calculation of the load as the product of the new flow rate data

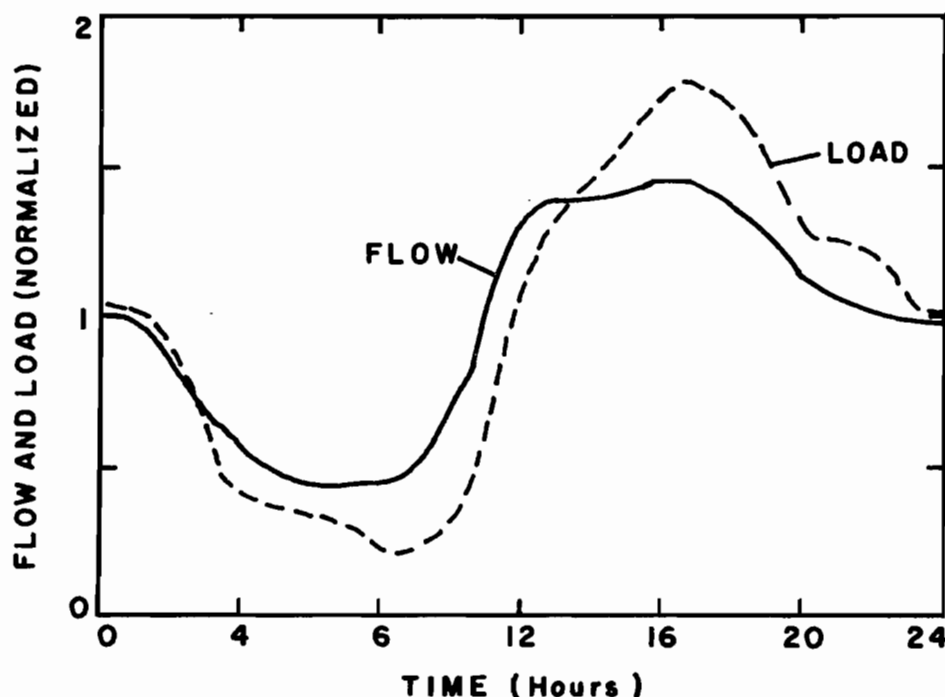


Fig 4.8 Goudkoppies WWTP influent flow rate and load patterns with a 2 hour phase change for the flow data (cf Fig 4.6).

and the same concentration data, and has an insignificant effect on the results.

Figure 4.9 shows a plot of the relative error, E_r , versus tank retention time, for the inputs of flow rate and load of Fig 4.8. As a comparison the curves of Fig 4.7 for the Cape Flats and the unaltered Goudkoppies data are also shown. From Fig 4.9 it is clear that, when the phase difference between the influent flow rate and load patterns for the Goudkoppies data is reduced to a value near to that for the Cape Flats data, the resulting shape of the curves for the Cape Flats and adjusted Goudkoppies data are very similar in form, i.e. the changes in shape of the E_r -retention time curves for different input patterns are primarily due to differences in phase of the flow and load input curves.

A general conclusion from Fig 4.9 is:

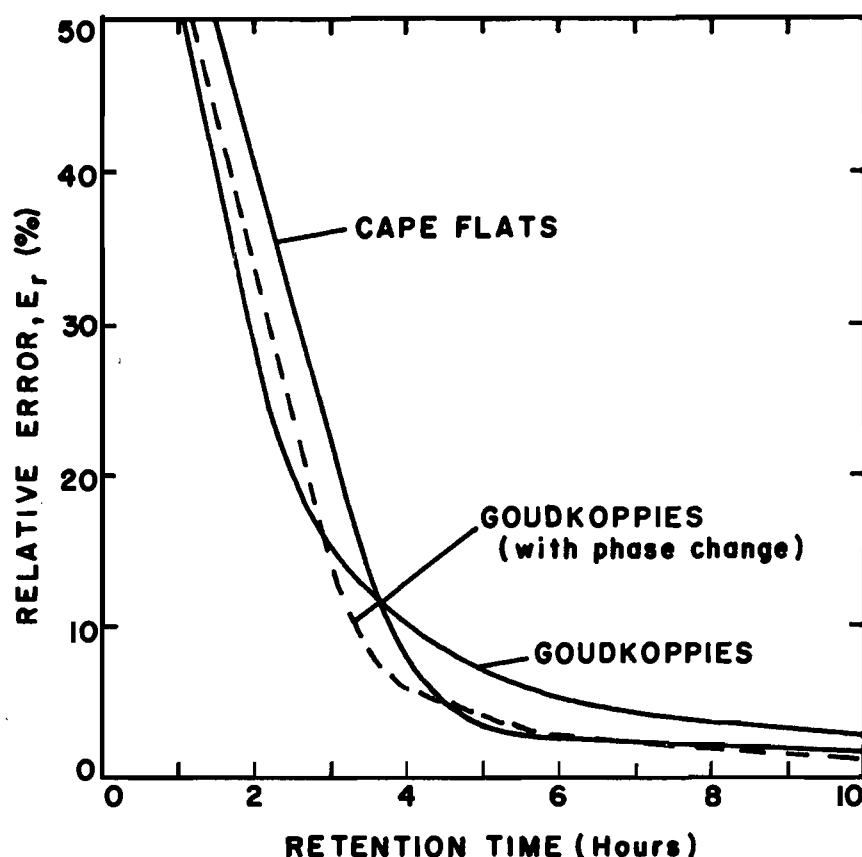


Fig 4.9 Comparison of the equalization efficiency with a reduction in the phase difference between the influent flow rate and load patterns.

- Irrespective of the form of the input patterns (within the limits normally encountered at WWTP's), the "optimum" retention time of the equalization basin appears to lie in the region of 4 to 6 hours.*

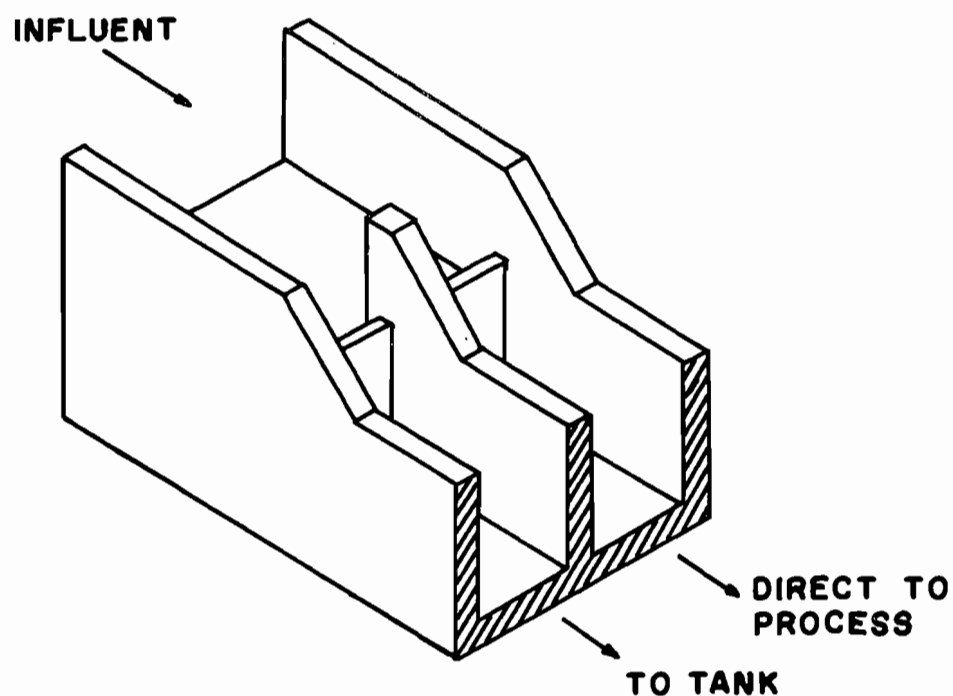
3. FACTORS AFFECTING EQUALIZATION EFFICIENCY IN SIDE-LINE EQUALIZATION

Incorporation of either an in-line or a side-line equalization scheme into a WWTP layout was illustrated in Fig 2.8. Whereas, with in-line equalization all the influent flow passes via the equalization basin to the downstream process, in side-line equalization only a portion of the flow is diverted via the basin while the remaining flow passes directly to the downstream process. In side-line equalization a choice is available regarding the method by which flow will be directed to the equalization basin. Basically, division of the influent flow can be achieved in two principal ways*, i.e.

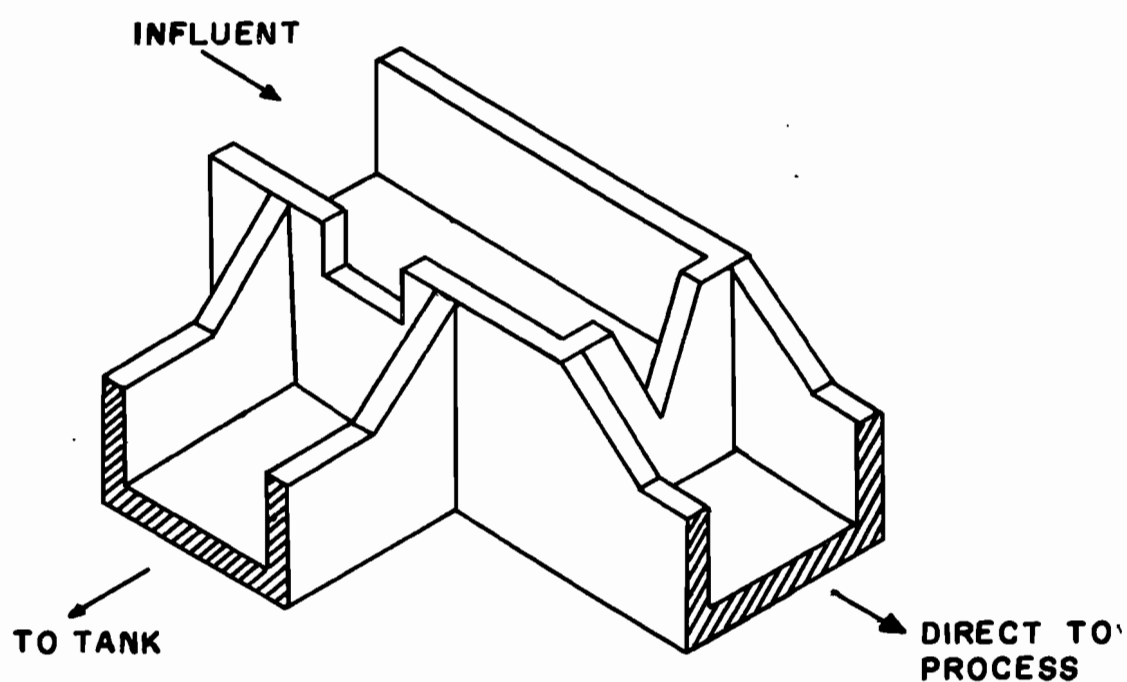
- (1) *Flow splitting*, where flow is divided in a fixed ratio as it passes over a weir [a typical physical arrangement by which this may be achieved is illustrated in Fig 4.10(a)]. At any instant a fixed proportion of the inflow is diverted to the equalization tank, while the balance passes directly to the downstream process.
- (2) *Flow topping*, where only flows above a certain rate are diverted to the equalization tank, while flows equal to or lower than the specified rate pass directly to the downstream process [see Fig 4.10(b)]. Figure 4.11 illustrates the division of flow obtained with flow topping where flows in excess of 0,75 units are diverted to the equalization basin, while the flow equal to or less than 0,75 units passes directly to the process.

In side-line equalization the function of the equalization algorithm is to develop the tank outflow rate profile (obeying the physical constraints), which, when mixed with the stream passing directly to

* In the literature there is confusion as to the terms applied to the different modes of flow division. Consequently, the usage of specific terms needs to be defined.



(a) FLOW SPLITTING



(b) FLOW TOPPING

Fig. 4.10 Schematic methods for implementing the modes of flow division considered in this investigation.

the downstream process, results in a mixed stream in which the deviations in flow rate and load from the respective mean values are minimized in terms of the error expression criteria. The two parameters which have a direct influence on equalization efficiency are (1) the fraction of the total influent flow that is diverted to the equalization tank, and (2) the retention time of the equalization tank. With regard to these parameters, two factors should be noted:

- In the analysis of the separate cases of flow splitting and flow topping it is necessary to quantify the division of the influent flow. To this end a *flow division factor*, γ , is defined. It should be noted that, for each case (splitting or topping) the definition of the flow division factor is different because the methods of flow division are different, i.e. a direct comparison between results for splitting or topping where the values of γ are equal is not valid.
- In this study tank retention time is specified in terms of the mean *total* influent flow rate to the equalization facility, and not in terms of the flow to the equalization tank only.

In addition to these observations it should be noted that in the simulations for side-line equalization which follow, the values of the weighting factors are again those listed in Table 4.1 where, *inter alia*, $\alpha = 0,5$ and equal weight is assigned to flow and to load equalization.

3.1 Flow Splitting

With flow splitting, where there is a continuous division of the inflow in a fixed proportion, the *flow division factor*, γ , is defined as the fraction of the inflow which passes directly to the downstream process, while the remaining fraction $(1 - \gamma)$ is routed via the equalization tank. The value of γ varies in the range from 0 to 1. In the extreme cases:

- (1) $\gamma = 0$, all the influent flow passes via the equalization tank;
this corresponds to in-line equalization; or if
- (2) $\gamma = 1$, the equalization tank is entirely by-passed.

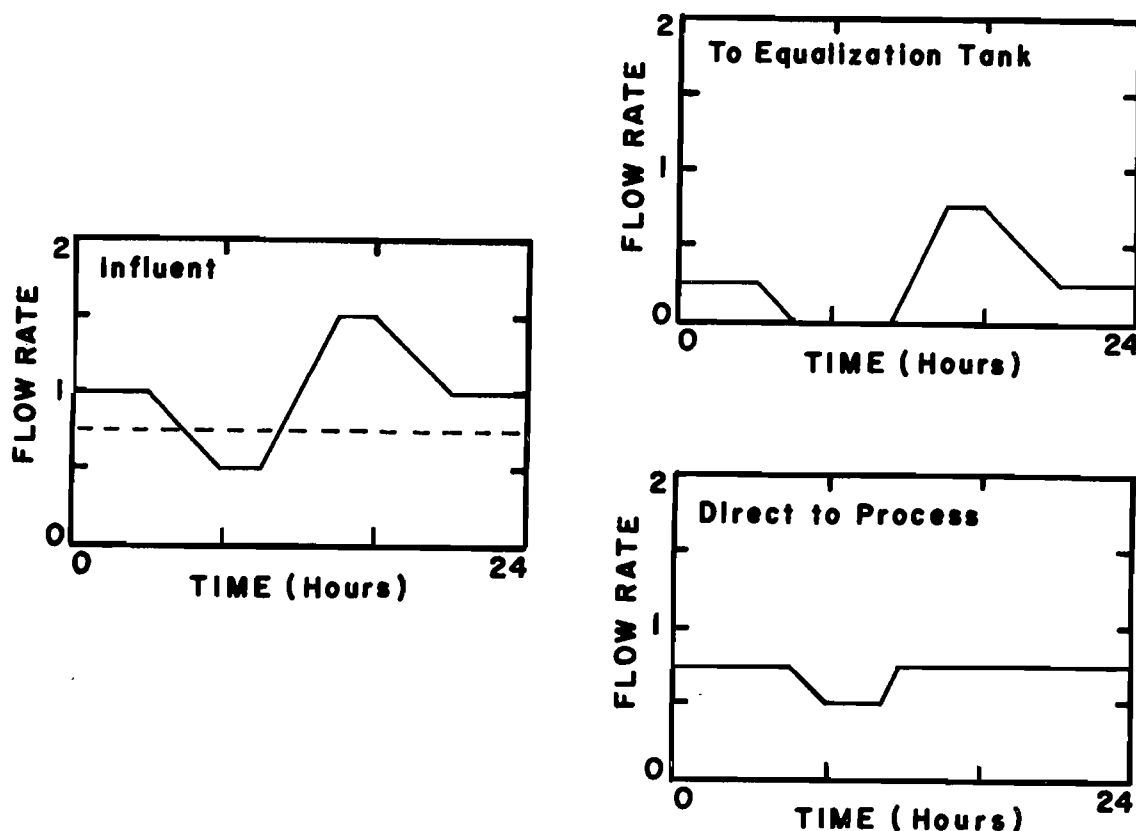


Fig 4.11 Division of influent flow by flow topping ($\gamma = 0,75$).

3.1.1 Effect of Equalization Tank Retention Time

In Fig 4.12 the relative error, E_r , is plotted versus equalization tank retention time, for a value of the flow division factor, $\gamma = 0,75$, i.e. 75 per cent of the influent flow continually bypasses the equalization tank. For purposes of comparison the curve of Fig 4.5 for in-line equalization ($\gamma = 0$) is shown in Fig 4.12 as a dotted line.

It is apparent that both curves are of the same form: the value of the relative error, E_r , decreases linearly with increasing tank retention time up to a certain point, after which there is change in the rate of decrease of the equalization error, and the relative error tends to level off to a constant value.

3.1.2 Effect of Flow Division Factor, γ

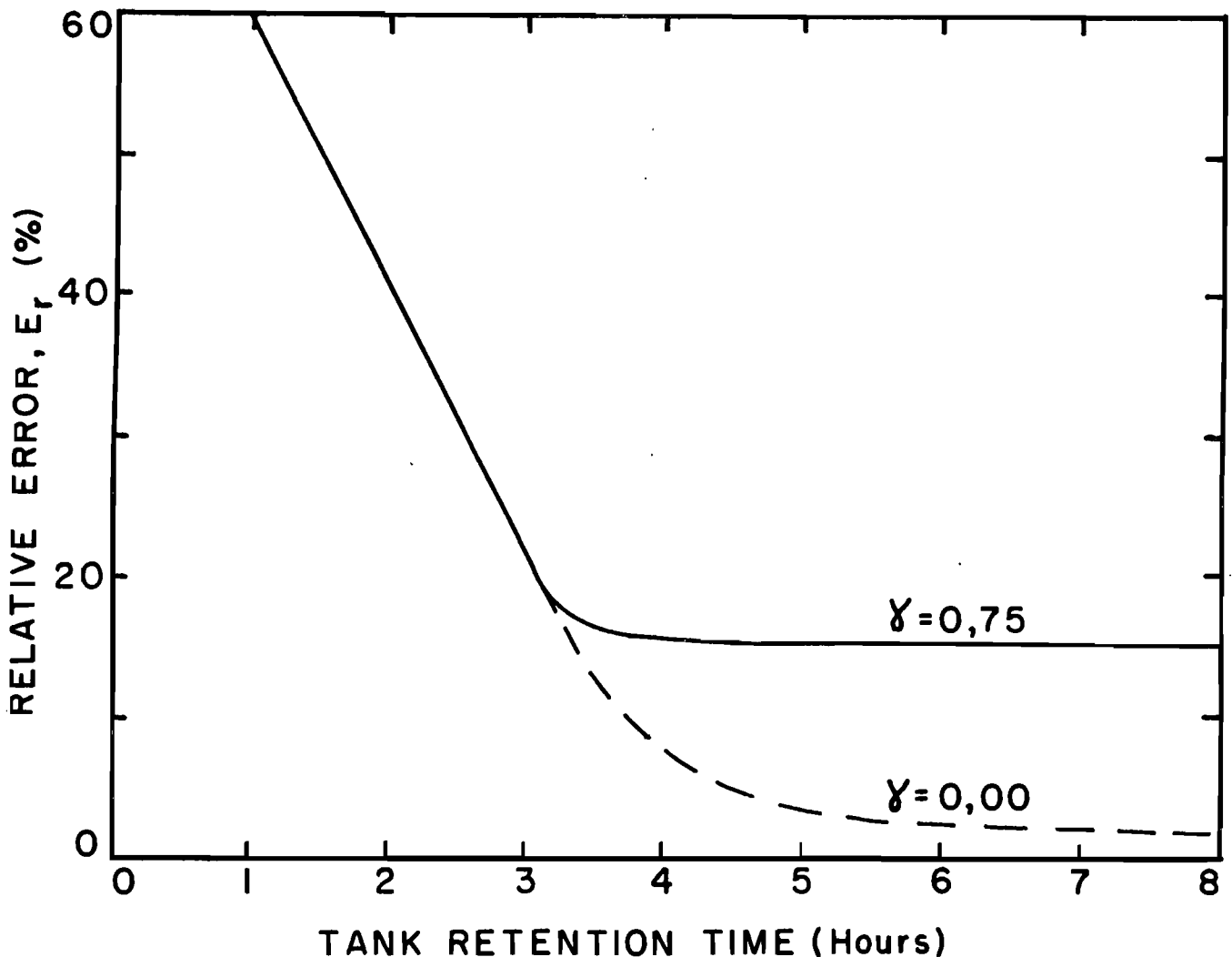


Fig 4.12 Effect of Equalization Tank retention time with flow splitting.

In Fig 4.13 the effect of the flow division factor, γ , on the equalization efficiency is shown by plotting a series of curves (similar to those shown in Fig 4.12), for different values of γ .

- (1) Irrespective of the value assigned to γ , each of the curves is of the same form, with the relative error levelling off to a nearly constant value with increasing tank retention time.
- (2) As the value of γ increases, i.e. as a larger fraction of the inflow bypasses the equalization tank, there is a decrease in the tank retention time at which the levelling off in relative error occurs.

- (3) As γ increases (i.e. as more flow bypasses the equalization tank) the curves level out at higher values of the relative error. For γ in the range of zero to about 0,6 there is very little increase in the relative error at which the curves level out (for the case considered), but as γ increases above 0,6 there is a marked increase in this value. This feature is more clearly illustrated when the results of Fig 4.13 are plotted in a different form. In Fig 4.14 the relative error, E_r , is plotted as abscissa versus the percentage of the influent flow diverted to the equalization tank (i.e. $(1-\alpha)$ as %) as ordinate, for tank retention times of 3, 4, 5 and 6 hours. From Fig 4.14, in all instances if more than 40 per cent of the inflow is continually diverted to the equalization tank the relative error remains virtually constant at a value fixed by the total mean retention time. That is, up to 60 per cent of the inflow may bypass the equalization tank without unduly influencing equalization efficiency.

3.1.3 Outflow Profiles

Up to this stage the results from application of the equalization algorithm to side-line equalization, with flow splitting, have been assessed only in terms of the relative error, E_r . This may be sufficient to identify important trends but it does not supply any information regarding two important aspects, i.e. (1) the form of the optimal tank outflow rate profile, and (2) the function of the equalization tank. These aspects become apparent when output of results is presented in graphical form.

To present the graphical output of results for side-line equalization an alternative computer plotting program to that used for in-line equalization (e.g. Fig. 4.1) is employed. A listing of the program (which utilizes the CALCOMP package), together with instructions for its application, is presented in Appendix B.

Figures 4.15, 4.16 and 4.17 show the results from application of the equalization algorithm, with values of the flow division factor, γ , of 0,10, 0,30 and 0,50, respectively, for the case of a 5 hour

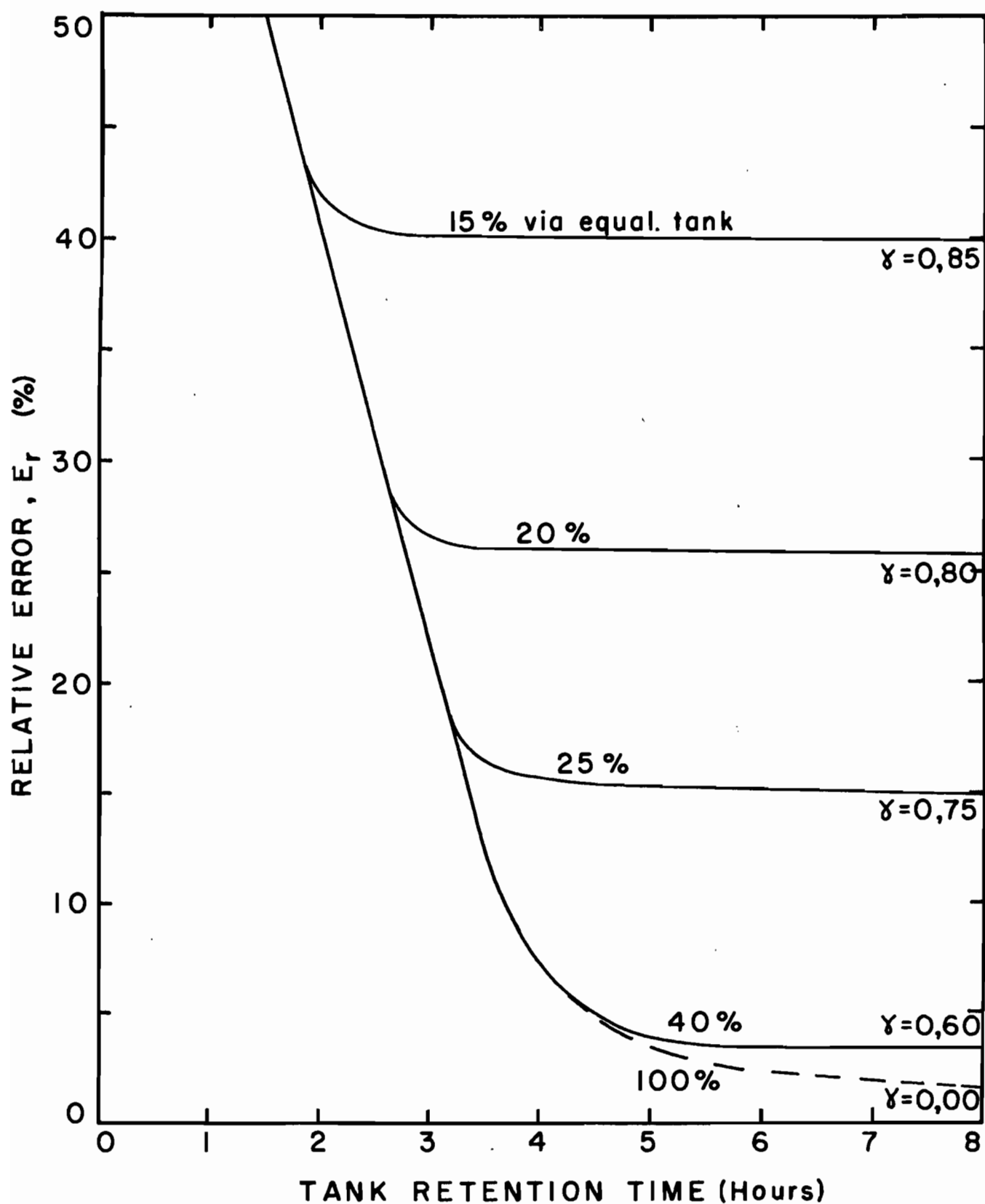


Fig. 4.13 Plots of relative error, E_r , (as a percentage) versus "side-line" equalization tank retention time, with flow division by flow splitting; flow division factor, γ , as parameter. (Cape Flats data).

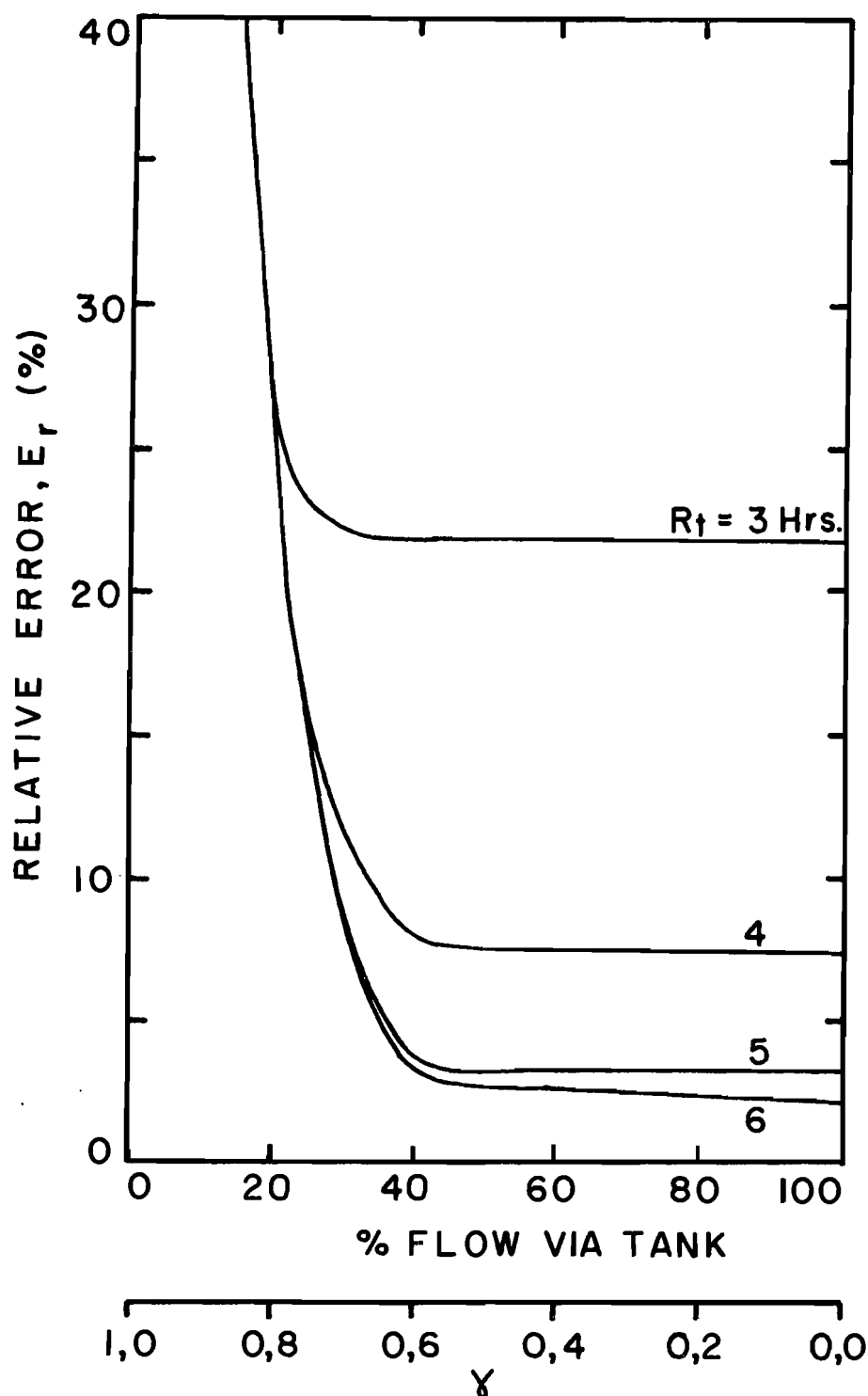


Fig. 4.14 Plots of the relative error, E_r , (as a percentage) versus the percentage of the influent flow diverted to a "side-line" equalization tank with flow splitting; tank retention time as parameter. (Cape Flats data).

CONFIG. : SIDE-LINE(FLOW SPLITTING)

TANK HOLD-UP = 5.0 HOURS CONSTANTS:

TANK LEVELS MAX = 100.0% ALPHA = 0.50

MIN = 0.0% GAMMA = 0.10

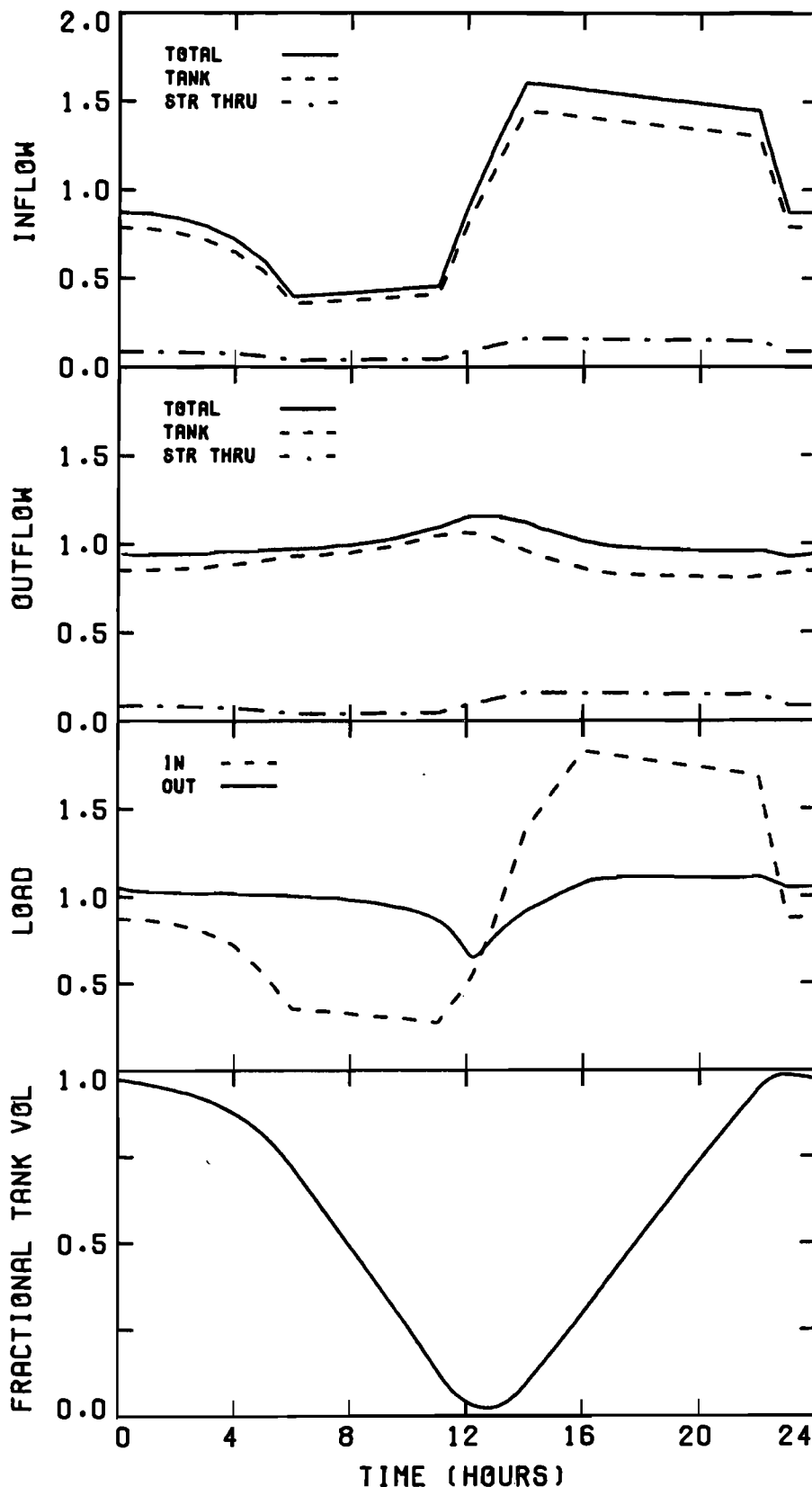


Fig. 4.15 Optimal results from application of the equalization algorithm to a 5 hour retention time "side-line" equalization tank, with flow splitting, under fixed diurnal input patterns of flow rate and load (Cape Flats data), where $\gamma = 0.10$.

CONFIG. : SIDE-LINE(FLOW SPLITTING)
TANK HOLD-UP = 5.0 HOURS CONSTANTS:
TANK LEVELS MAX = 100.0% ALPHA = 0.50
 MIN = 0.0% GAMMA = 0.30

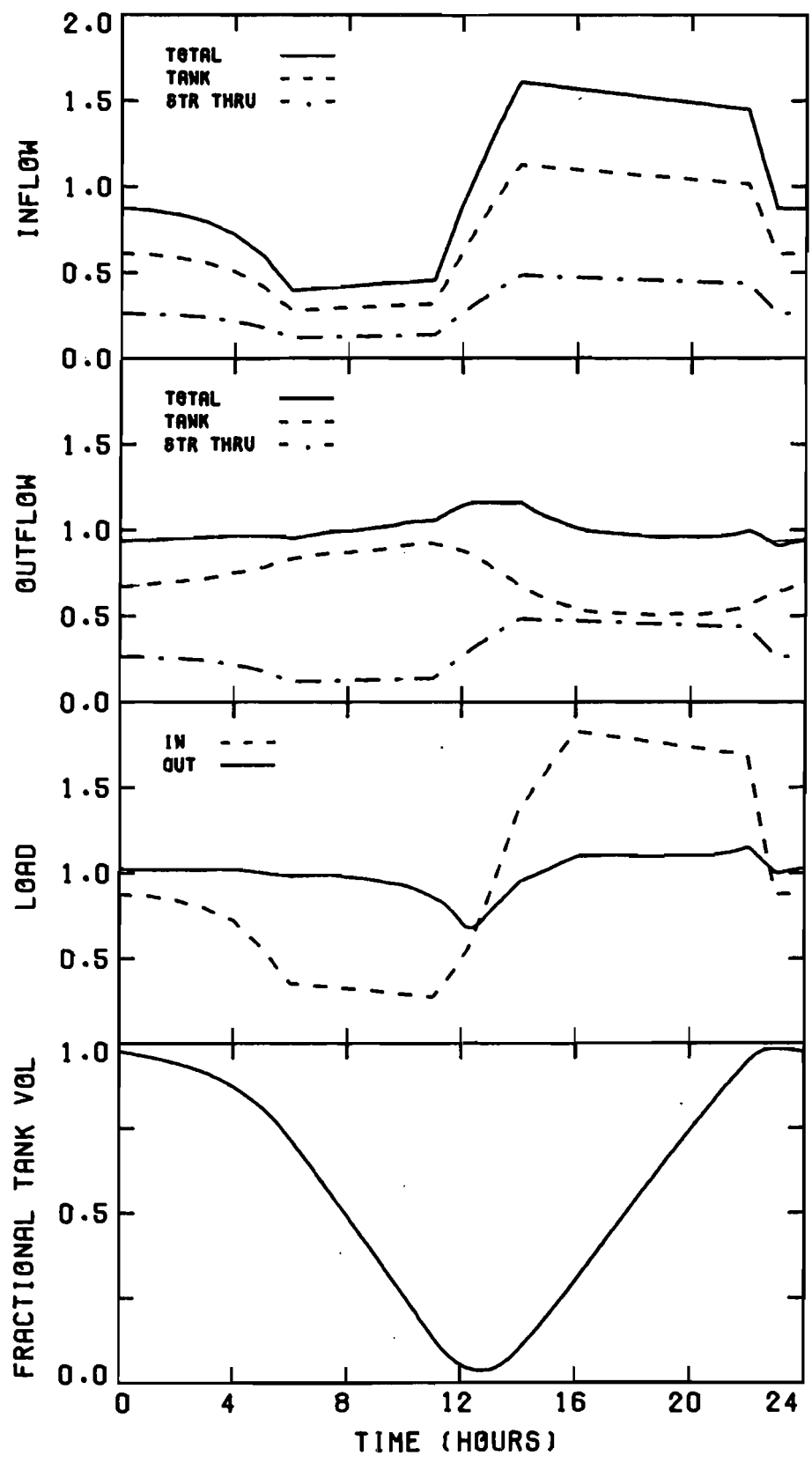


Fig. 4.16 Optimal results from application of the equalization algorithm to a 5 hour retention time "side-line" equalization tank, with flow splitting, under fixed diurnal input patterns of flow rate and load (Cape Flats data), where $\gamma = 0.30$.

CONFIG. : SIDE-LINE(FLOW SPLITTING)
 TANK HOLD-UP = 5.0 HOURS CONSTANTS:
 TANK LEVELS MAX = 100.0% ALPHA = 0.50
 MIN = 0.0% GAMMA = 0.50

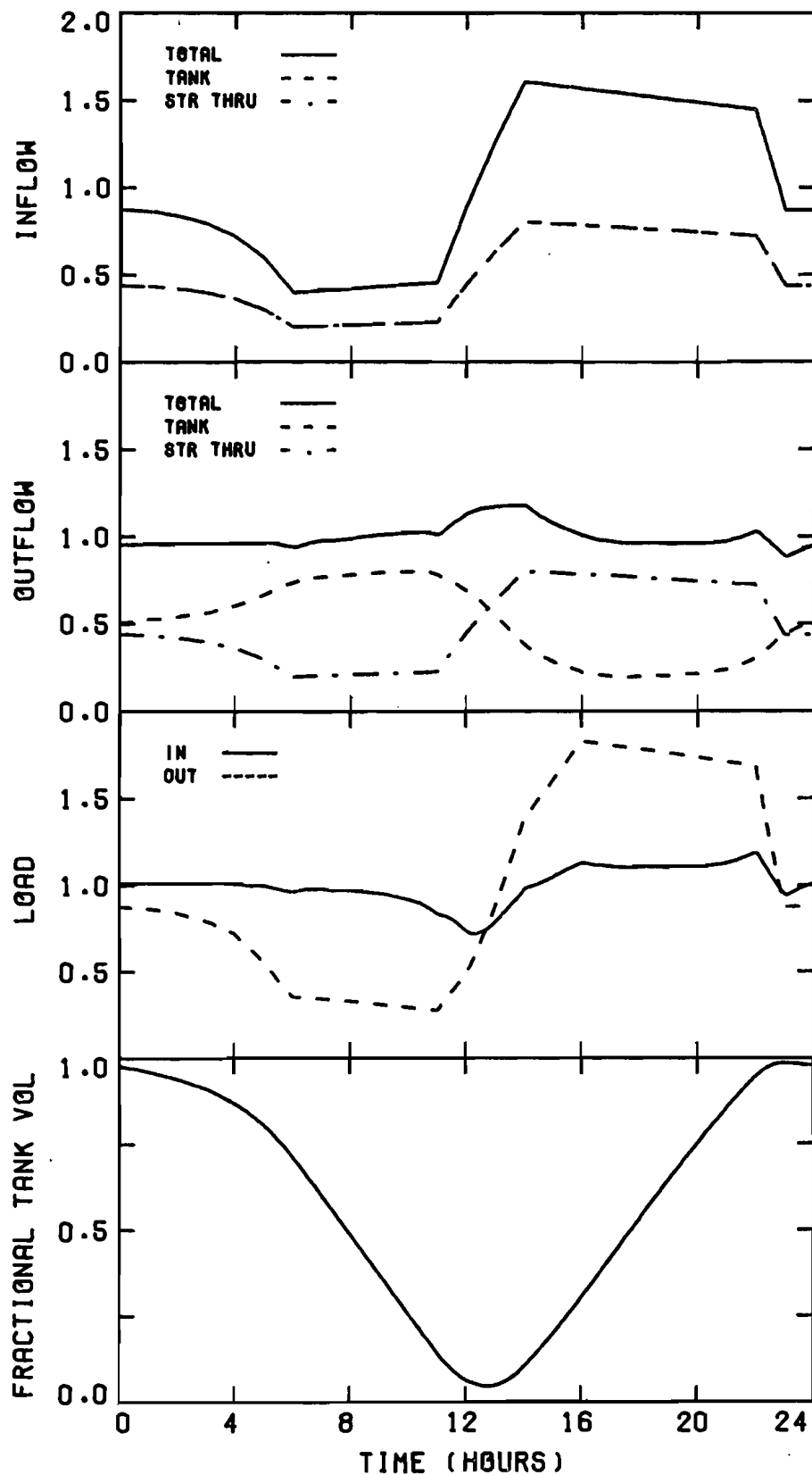


Fig. 4.17 Optimal results from application of the equalization algorithm to a 5 hour retention time "side-line" equalization tank, with flow splitting, under fixed diurnal input patterns of flow rate and load (Flats data), where $\gamma = 0.50$.

retention time equalization tank. Each figure is subdivided into four sections:

- (1) The top section shows the division of the total *influent* flow over the day into two streams, one of which is diverted to the equalization tank while the other passes directly to the downstream process.
- (2) The next lower section shows the division of the total *outflow* rate from the equalization installation, comprised of the two component streams; (a) the stream passing directly to the downstream process, and (b) the outflow from the equalization tank.
- (3) The third section in the figure allows a comparison between the total *influent load* profile and the total *effluent stream load* profile from the equalization installation.
- (4) The lower section shows the variation in tank hold-up over the day resulting from application of the optimization procedure.

In Fig 4.15, where the flow division factor, γ , has a value of 0.10, i.e. only 10 per cent of the influent flow to the installation passes directly to the downstream process; at all times the flow rate of this stream by-passing the equalization tank is small relative to the outflow rate from the equalization tank. It is evident that when γ is small, the major portion of the influent equalization error, $(E_e)_{in}$, is passed to the equalization tank; the major contribution to the effluent equalization error, $(E_e)_o$, of the mixed outlet stream (tank outflow plus "straight through" stream) therefore can be expected to arise in deviations in the flow rate and load from their respective mean values in the tank outflow stream. Thus, when γ is small, the action of the equalization algorithm essentially is to develop the tank outflow rate profile in such a way that deviations in flow rate and load, from their mean values, are minimized in the tank outlet stream. That is, when γ is small, the tank outflow rate and effluent load profiles are similar to those for in-line equalization, utilizing a tank of the same retention time. This similarity is verified by comparing Figs 4.15 and 4.3, where Fig 4.3 is an in-line facility with

the same retention time as that used in Fig 4.15.

With an increase in the flow division factor, γ , (i.e. as a greater portion of the influent flow passes directly to the downstream process) the stream passing directly downstream transmits an increased portion of the influent equalization error. The action of the equalization algorithm changes from that of smoothing the *tank* effluent flow rate and load profiles to that of counteracting the error transmitted in the stream bypassing the equalization tank. The increasing counter-acting effect is clearly evident in Figs 4.16 and 4.17 where γ increases from 0,30 to 0,50. In fact, at high γ the tank outlet stream tends to the mirror image of the bypassing stream.

3.2 Flow Topping

In a side-line equalization facility, when the mode of flow division is flow topping, it should be noted that the flow division factor, γ , has a different meaning to that of γ in the case of flow splitting (see Section 4.1). With flow topping γ is defined such that all flows greater than γF_{av} are diverted to the equalization basin (where F_{av} = mean daily influent flow rate). Thus, for an influent flow rate, F , at some instant:

- (i) If $F < \gamma F_{av}$, then no flow is diverted to the equalization tank, and the flow rate of the stream passing directly to the downstream process is F .
- (ii) If $F > \gamma F_{av}$, then the flow rate of the stream passing to the equalization tank is $(F - \gamma F_{av})$, and the flow rate of the stream passing directly to the downstream process is γF_{av} .

The value of γ can be specified in the range from 0 up to a value such that the product γF_{av} equals the maximum influent flow rate, F_{max} , over the day. In the extreme cases, if:

- (i) γ equals zero, all the influent flow passes via the equalization tank, i.e. in-line equalization;
- (ii) γF_{av} equals or exceeds the maximum influent flow rate, F_{max} , no flow is diverted to the equalization tank.

The effects of equalization tank retention time and the value of the flow division factor, γ , when utilizing flow topping in side-line equalization, are now considered separately.

3.2.1 Effect of Equalization Tank Retention Time

Plots of the relative error, E_r , versus the tank retention time, for values of the flow division factor, γ , of 0,50, 1,00, 1,10 and 1,20 are shown in Fig 4.18. For purposes of comparison, the base case where γ equals zero (corresponding to in-line equalization) is shown as a dotted line. Characteristically, the relative error, E_r , decreases linearly with increasing tank retention time up to a certain retention time; at longer retention times there is a fall off in the rate of decrease of E_r , and E_r tends to level out to a constant value.

3.2.2 Effect of the Flow Division Factor, γ

Figure 4.18 also illustrates the effect of γ on the equalization efficiency. Comparing the relative error curves for different γ values, it is evident that:

- (1) For the particular influent flow rate and mass loading pattern considered here, irrespective of the tank retention time, as the value of γ increases from 0 to about 0,50 there is a slight *improvement* in the value of the relative error, E_r , at all retention times.
- (2) For each value of γ the curves level out to an essentially constant value of E_r as the retention time increases. For values of γ between 0 and about 0,5 the constant value of E_r remains virtually unchanged (at a low value). As γ increases to 0,60 and above, the value of E_r at which the curves level out to a constant value *increases* rapidly.

The behaviour noted in (1) and (2) above is illustrated more clearly when the results in Fig 4.18 are re-plotted, relative error, E_r , versus flow division factor, γ , holding the tank retention time constant. This is shown in Fig 4.19 for tank retention times of 3, 4, 5 and 6 hours. From Fig 4.19 it is apparent that:

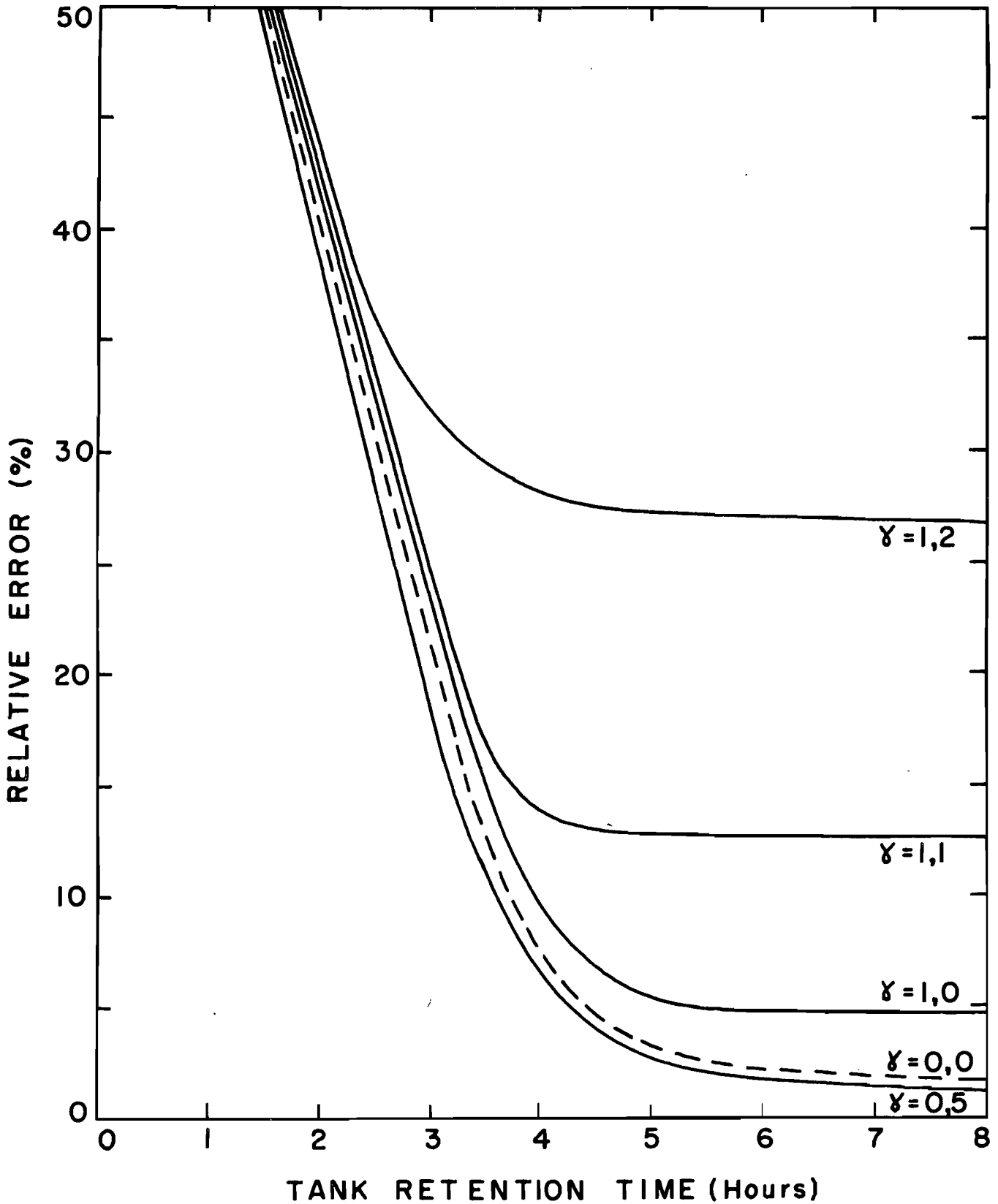


Fig. 4.18 Plots of relative error, E_r , (as a percentage) versus "side-line" equalization tank retention time, with flow division by flow topping; flow division factor, γ , as parameter. (Cape Flats data).

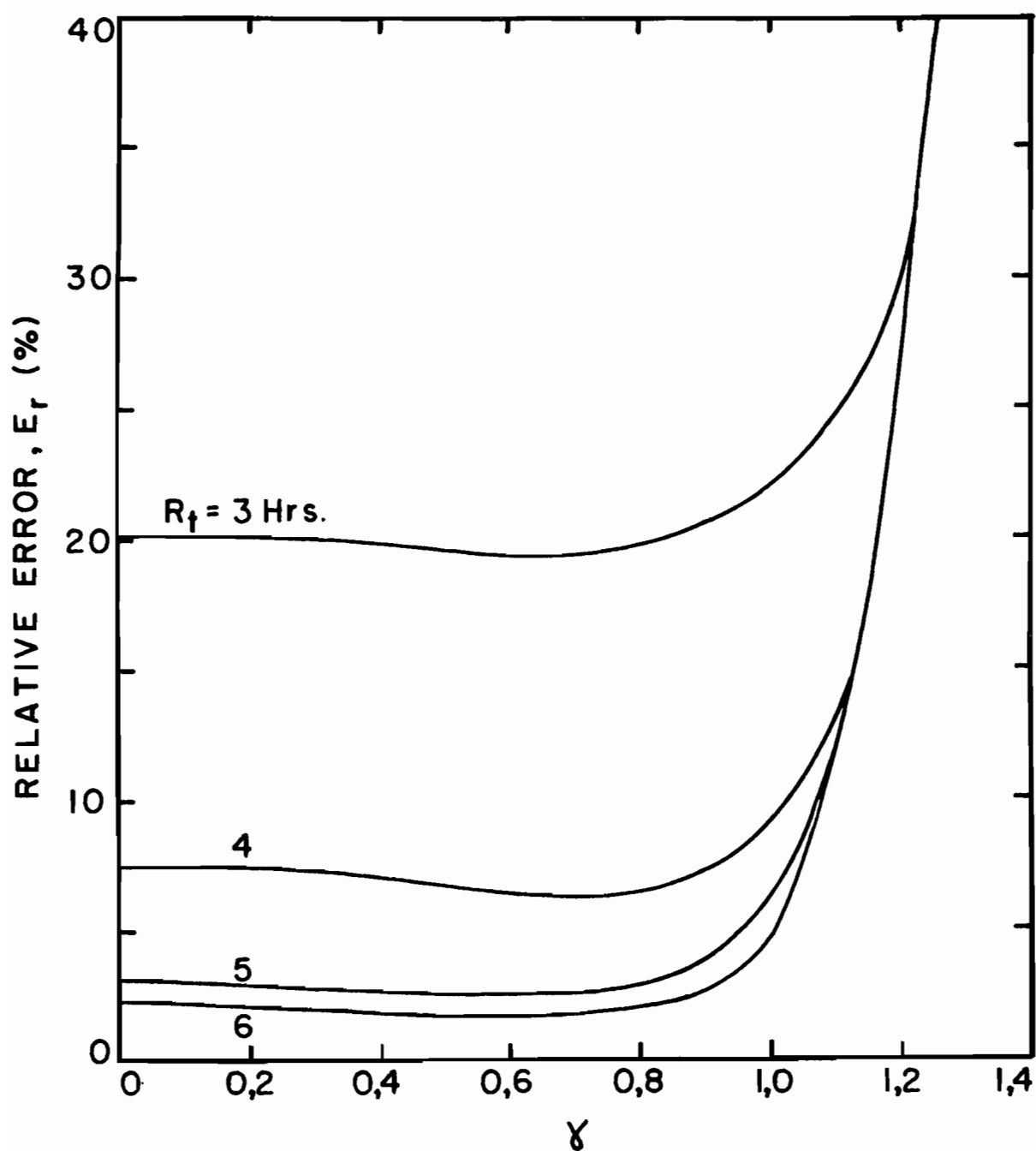


Fig. 4.19 Plots of the relative error, E_r , (as a percentage) versus the flow division factor, γ , in "side-line" equalization with flow division by flow topping; tank retention time as parameter. (Cape Flats data).

- (1) For any selected retention time, for values of γ greater than about 1,0, there is a rapid increase in the relative error, E_r^* .
- (2) For any selected retention time there is an optimum value of γ in the range of 0,5 to 0,8 (for this case) which minimizes the relative error, E_r .
- (3) As the tank retention time increases above 5 hours, there is only a slight improvement in the equalization efficiency.

The fact that, for a specified tank retention time, a value of γ in the range of about 0,5 to 0,8 results in an optimum (minimum) relative error, can be explained in terms of a relative improvement in load equalization. In the case being considered, when γ has a value of 0,60, the flow rate of the stream passing directly to the downstream process is almost constant; the flow rate only drops slightly below γ over the period from 05h00 to 11h00. The major portion of the flow diverted to the equalization tank enters the process between 11h00 and 23h00. Considering the influent load pattern, it is apparent that, over this period, the flow being diverted to the equalization tank is of a relatively high concentration. Thus, the liquid contained in the equalization tank may be regarded as having a high load equalizing potential, and the outflow from the equalization tank potentially may be distributed in such a manner that a slightly greater degree of load equalization is achieved in the mixed stream than could have been achieved were the equalization tank concentration lower.

The function of the side-line equalization tank changes as the value of the flow division factor, γ , increases. Information in this regard is obtained by considering the division of flow into and out of the equalization facility. Comparison of Figs 4.20, 4.21 and 4.22,

* In this respect it is of interest to note that, in practice, a value of $\gamma = 1,0$ is usually employed, i.e. only flows in excess of the average daily inflow are diverted to the equalization tank. In light of the analysis here a value of $\gamma \leq 0,8$ is preferable, i.e. all flows greater than 0,8, say, of the mean should be diverted to the equalization tank.

where γ is assigned values of 0,30, 0,50 and 0,70, respectively, illustrates the changing function of the equalization algorithm with changing γ . When the value of γ is 0,30, the flow rate of the stream passing directly to the downstream process is constant. In equalizing the flow and load, the function of the equalization tank is principally to smooth the flow variations entering the tank. Since this flow is relatively smaller when compared to the in-line case, it is possible for the algorithm to utilize the available tank volume more effectively and thus reduce the relative error. As the value of γ increases to 0,50 and 0,70 (Figs 4.21 and 4.22, respectively), deviations in the flow rate of the stream passing directly to the downstream process become more marked and the function of the equalization algorithm is not so much to smooth the *tank* effluent flow and load profiles, but rather to develop the tank outflow rate profile in such a manner that the "gaps" in the flow passing directly to the downstream process are "filled", i.e. the outflow pattern of the stream from the equalization tank is inverted with respect to the flow rate pattern of the stream passing directly to the downstream process.

4. CHOICE OF EQUALIZATION FACILITY CONFIGURATION

Sections 2 and 3 deal separately with in-line equalization and side-line equalization (with flow division either by splitting or topping). A comparison of Figs 4.5, 4.13 and 4.18 illustrates that, under fixed diurnal influent flow and load rate patterns, and with the appropriate selection of process parameters, side-line equalization with flow topping theoretically provides the most efficient equalization as measured in terms of the relative error, E_r . The difference, however, is marginal provided the equalization tank has a retention time of about 5 hours or greater. At 5 hours or greater the process parameters for any of the three systems may be selected in such a manner that the effluent equalization error is reduced to about 3 per cent of that of the influent, i.e. $E_r = 3\%$. The relative error, E_r , therefore, should not form the sole basis for selection of an equalization system. This requires that other factors be identified to provide a basis for the selection.

CONFIG. : SIDE-LINE(FLOW TOPPING)
 TANK HOLD-UP = 5.0 HOURS CONSTANTS:
 TANK LEVELS MAX = 100.0% ALPHA = 0.50
 MIN = 0.0% GAMMA = 0.30

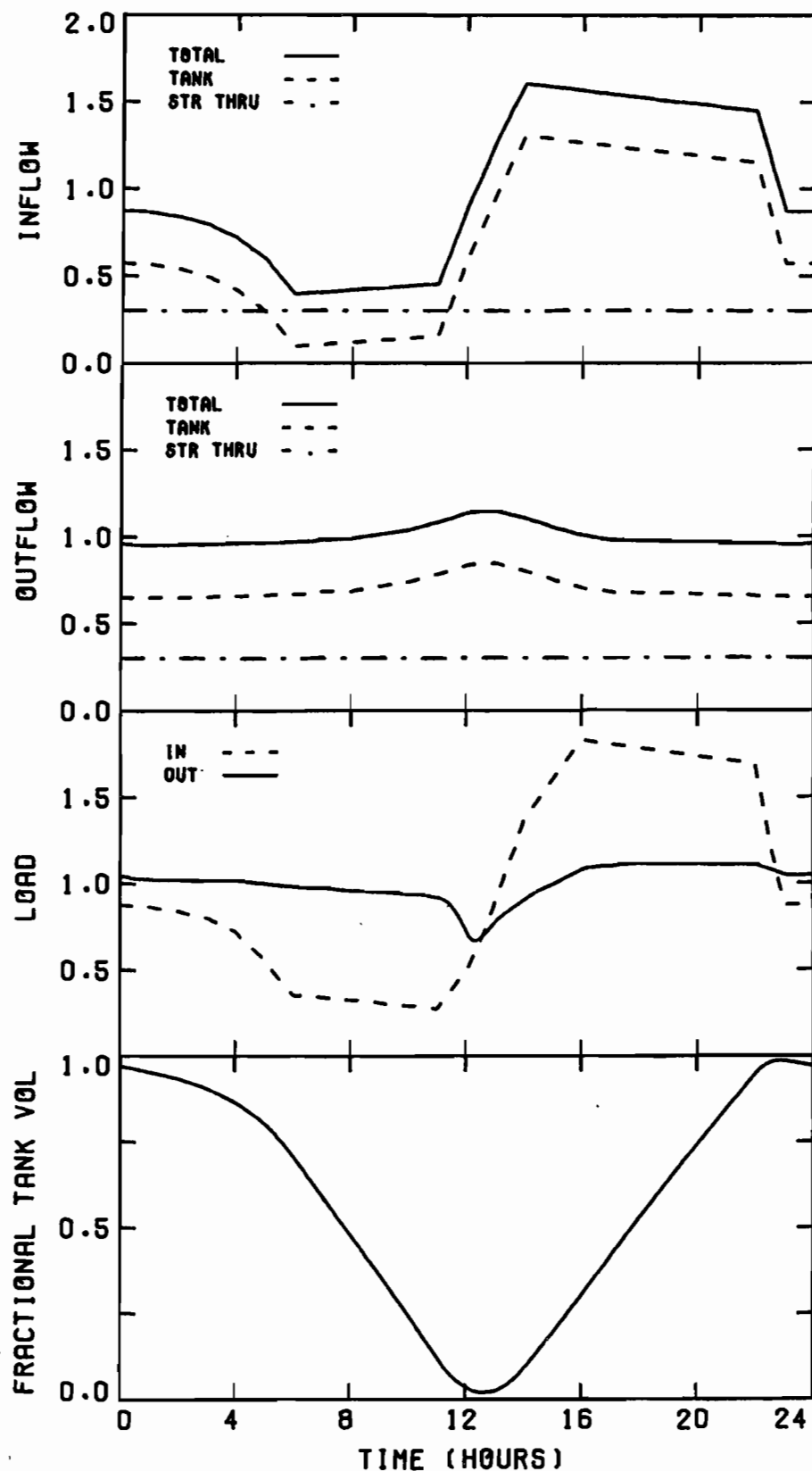


Fig. 4.20 Optimal results from application of the equalization algorithm to a 5 hour retention time "side-line" equalization tank, with flow topping, under fixed diurnal input patterns of flow rate and load (Cape Flats data), where $\gamma = 0.30$.

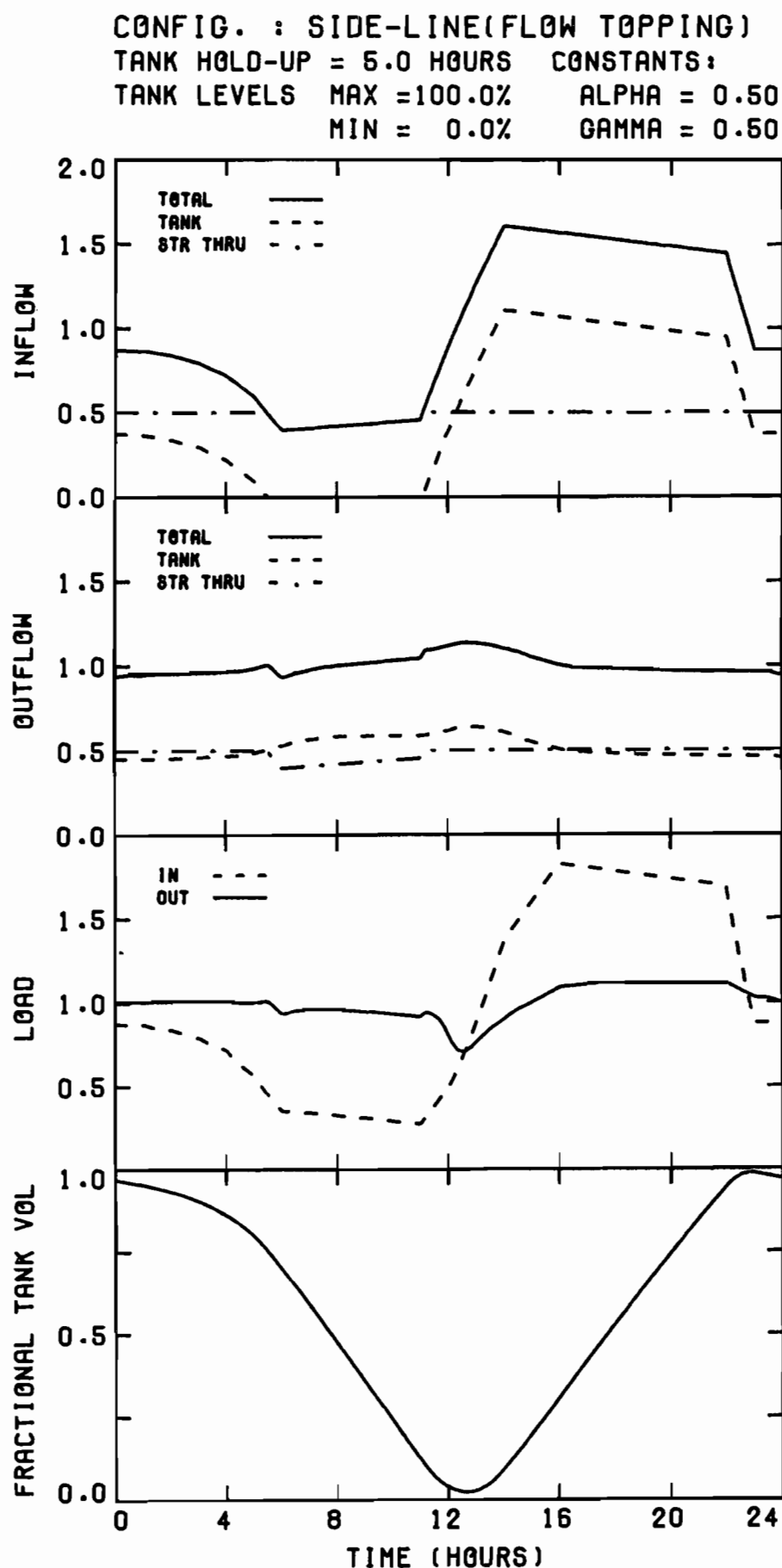


Fig. 4.21 Optimal results from application of the equalization algorithm to a 5 hour retention time "side-line" equalization tank, with flow topping, under fixed diurnal input patterns of flow rate and load (Cape Flats data), where $\gamma = 0.50$.

CONFIG. : SIDE-LINE(FLOW TOPPING)
 TANK HOLD-UP = 5.0 HOURS CONSTANTS:
 TANK LEVELS MAX = 100.0% ALPHA = 0.50
 MIN = 0.0% GAMMA = 0.70

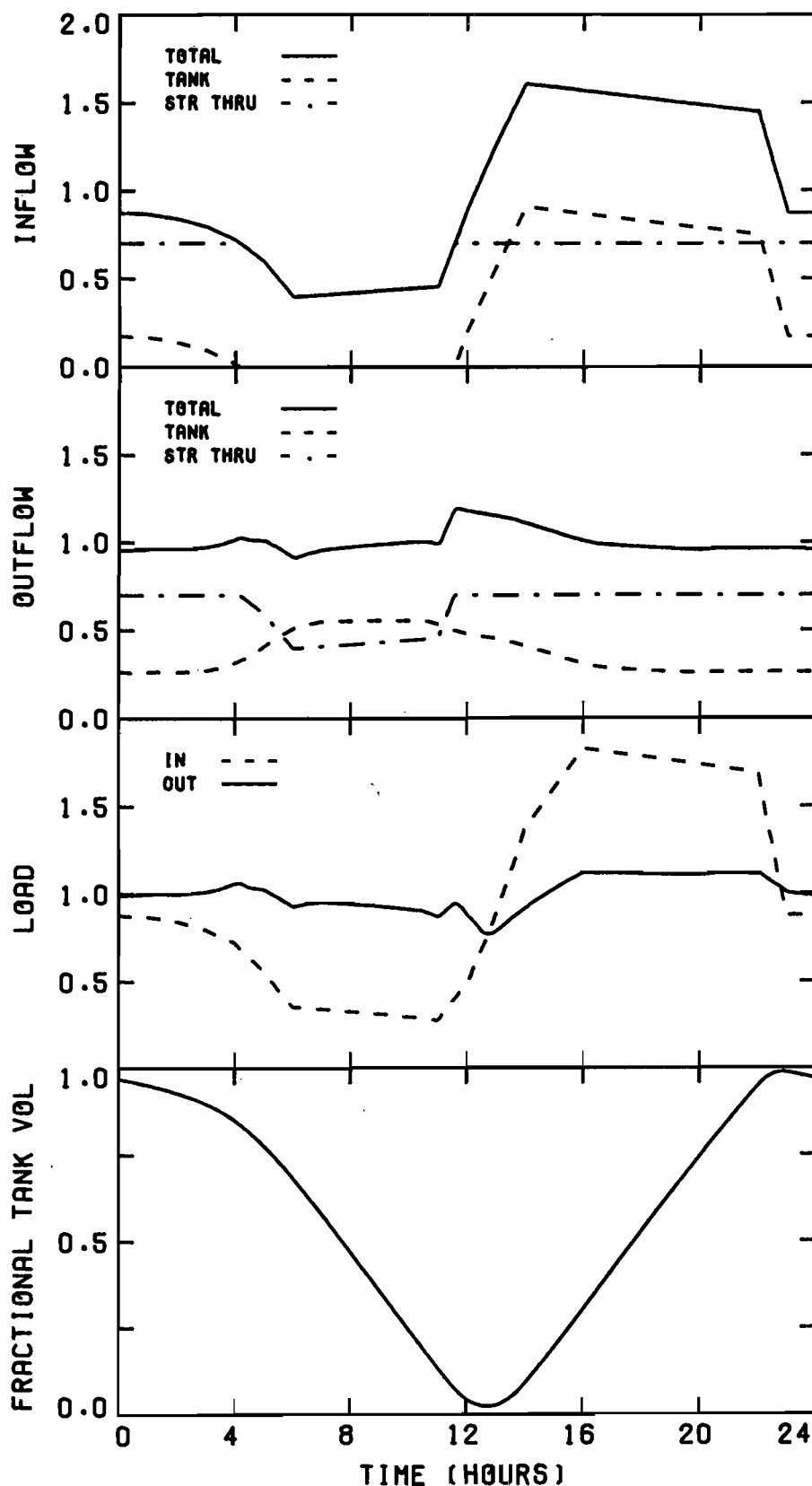


Fig. 4.22 Optimal results from application of the equalization algorithm to a 5 hour retention time "side-line" equalization tank, with flow topping, under fixed diurnal input patterns of flow rate and load (Cape Flats data), where $\gamma = 0.70$.

One factor favouring the choice of a side-line configuration as opposed to an in-line configuration is the possible saving in pumping costs. If the layout and topography is such that the flow to or from the equalization tank needs to be pumped, then side-line equalization may be preferable as only about 40 per cent of the daily influent flow needs to be diverted to the equalization tank. This may result in a considerable saving in both pumping capital costs and power requirements.

Side-line equalization, however, has one adverse feature which becomes apparent when one considers the practical operation of such a facility. Consider, say, the operation of a side-line equalization tank with flow division by splitting:

In practice (1) the form of the influent flow and load patterns change slightly from day to day, and (2) rapid random variations are superimposed on the daily cyclic pattern. With flow splitting there is a continual division of the inflow so that any rapid variations continually will be similarly divided. Considering the stream which is diverted to the equalization tank, the equalization algorithm, which develops a smooth tank outflow rate profile, will ensure that the equalization tank acts as a buffer to rapid variations in this stream. However, the rapid random variations in the stream bypassing the equalization tank will be transmitted to the downstream process. Depending on the amplitude of the variations and the fraction of the influent flow bypassing the equalization tank, the random fluctuations in the bypass will negate, to a degree, the objective of equalization in that the downstream process will not receive a stream which is smooth in terms of either flow or load.

The problem identified above will arise at all times during the cycle when the division of flow is by splitting as a portion of the inflow continually bypasses the equalization tank. In the case of flow topping, however, random fluctuations in both flow and load will be passed on only over those parts of the daily cycle when the whole influent flow is passed directly to the downstream process, i.e. when the inflow drops to a value less than γ of the mean daily inflow;

over the remainder of the cycle the flow rate of the stream bypassing the tank is constant so that only random concentration fluctuations still will be bypassed downstream. In this respect, flow topping appears to be more attractive than flow splitting, providing the flow division factor, γ , is selected appropriately.

Where pumping costs are not a consideration, i.e. the topography allows gravity flow through the equalization facility, the in-line configuration appears to be the preferable one. Not only does this ensure that rapid variations in flow and load in the influent stream are damped, but also the installation layout is more simple and hence likely to be less costly.

With regard to equalization tank volume requirements, comparison of in-line and side-line equalization indicates that, in the region where effective equalization is achieved, both schemes require the same size of equalization tank, i.e. *neither scheme results in a reduced tank volume requirement over the other.*

CHAPTER FIVE

DEVELOPMENT OF AN EQUALIZATION CONTROL STRATEGY

1. INTRODUCTION

The essence of the control problem in equalization is to determine the appropriate outflow rate from the equalization tank at any time such that variations in flow rate and/or load rate will be optimally minimized. In Chapter 3 it was stated that to accomplish control requires the development of

- an *equalization algorithm*, and
- a *control strategy* which incorporates the equalization algorithm.

The equalization algorithm developed in Chapter 3 does not constitute a control strategy for the real-time operation of an equalization facility. The results obtained from application of the tank outflow profile development algorithm provide an ideal solution; the assumptions are made that (1) there are known daily cyclic patterns of flow and load, and (2) these patterns are repeated identically from day to day i.e. all the parameters associated with the tank response (effluent flow and load rates and tank hold-up) are the same at the beginning and the end of each day. These assumptions do not provide a basis for solution of the practical problem of operating an equalization installation where (1) random variations about the mean daily cyclic influent flow and load rate patterns are encountered, (2) the patterns are not repeated identically from day to day, and (3) specific changes in the daily inputs occur on a weekly and seasonal basis. From these observations it is apparent that the procedure for the control of an equalization facility involves two aspects:

- A procedure for utilizing the equalization algorithm which will lead to efficient equalization on a continuous basis.
- A procedure for determining, with satisfactory accuracy, the

influent patterns for a 24-hour cycle for use by the equalization algorithm.

Development of these procedures is now discussed. Because the two aspects are independent of one another each may be handled separately. In this study incorporation of the equalization algorithm in a control strategy will be considered first, accepting the existence of a procedure for determining the expected influent profiles.

2. INCORPORATION OF EQUALIZATION ALGORITHM IN A CONTROL STRATEGY

The equalization algorithm presented in Chapter 3 was developed with the express intention of incorporating the algorithm in a control strategy for the real-time operation of an equalization installation. For this reason attempts were made to structure the equalization algorithm in a manner which would facilitate its incorporation in a control strategy. It was envisaged that in the control of an equalization tank, where the tank outflow rate is the controlled parameter, adjustments to the outflow rate would be made at intervals over the day. With this in mind, in the equalization algorithm the 24-hour cycle was divided into a number of "improvement" intervals; application of the algorithm under known 24-hour influent flow rate and load patterns involves an iterative procedure whereby incremental changes are made to an initial outflow profile at the different "improvement" intervals until an optimal condition is obtained.

In the development of the control strategy the same approach is used; the 24-hour cycle is divided into a number of control intervals, equal to the number of "improvement" intervals utilized in the equalization algorithm. Operation of the control strategy may briefly be described as follows:

At the beginning of a control interval the tank outflow rate for the interval must be determined; this outflow rate must lead to optimal equalization of flow and load (in terms of

the specified criteria) not necessarily over that particular interval, but rather, as a part of the whole 24-hour cycle. The approach is to determine the expected influent flow and concentration patterns for the ensuing 24-hour cycle; then, taking into account the tank hold-up and concentration at that time, these expected influent patterns are utilized by the equalization algorithm to compute the optimal outflow profile for the next 24 hours. The outflow rate for the control interval is then set equal to that for the corresponding "improvement" interval from the optimum profile.

The sequence above has to resolve the following problem: The expected influent profiles for the ensuing 24-hour cycle are unlikely to be identical to the actual influent profiles over that period. However, by repeating the procedure outlined above at regular intervals, and at each point taking into account the tank hold-up and concentration at that time, performance of the equalization tank is continuously optimized; this approach should lead to near-optimal performance in an on-going manner.

Before describing the iterative control procedure in more detail certain features concerning the use of the equalization algorithm in the control strategy should be discussed.

2.1 Considerations Regarding use of Equalization Algorithm in Control Strategy.

When utilizing the equalization algorithm in the control strategy a change is necessary in the mechanism of adjusting the outflow rate at an "improvement" interval during the iterative optimization procedure: In Section 3.2.2, Chapter 3, the mechanism by which a single change is made to the outflow rate profile involved making a linear change in flow rate over the "improvement" interval under consideration, with a linear change in flow rate over the following

interval and in addition, it was necessary that the remainder of the outflow rate profile be adjusted in an opposite direction in order to obey material balance principles (see Fig. 3.1, Chapter 3). That is, it was necessary to ensure that the total tank outflow over the day equalled the inflow. The result of the mechanism by which individual changes were made to the outflow rate profile was a continuously changing smooth curve (e.g. Fig. 4.1). The change to the mechanism used in the control strategy involved (1) changing the *form* of the adjustments made to the outflow over the "improvement" interval in the iterative optimization procedure, and (2) dropping the requirement to make slight adjustments to the remainder of the outflow rate profile in order to maintain a material balance.

- (1) Form of incremental flow rate adjustments: Irrespective of whether the flow is pumped from the equalization tank or flows by gravity, it is most probable that the outflow rate over a control interval will be near constant. That is, the actual outflow rate from the tank will consist of a series of constant rates with discontinuities where there is a change in flow rate, i.e. a step function. For this reason it is desirable that the profile utilized by the equalization algorithm in the control strategy should be in step function form, and, that changes made to the profile at an "improvement" interval should consist of changing the outflow rate over the duration of the interval by a constant incremental amount (starting with a profile which is constant over the whole cycle). In the limit, as both (1) the length of the intervals, and (2) the magnitude of the incremental changes decrease, the outflow rate will approximate a continuous curve. The selection of the length of the control interval and the magnitude of the incremental change utilized by the equalization algorithm will be discussed later.
- (2) Consideration of material balance principles: To understand why it is no longer appropriate to strictly maintain a material balance *over 24 hours* with each adjustment to the outflow

rate profile when applying the equalization algorithm in the control strategy, it is necessary to consider the development of the algorithm. Initially the algorithm was developed (and tested) under invariant daily input patterns of flow and load; the implication was that the influent patterns are repeated identically from day to day. The intention was to obtain a dynamic steady state where (1) at the beginning and end of each day, the variables associated with the tank response (hold-up and concentration) are the same, and (2) the daily inflow equals the daily outflow. To identify the optimal equalization solution there is no foreknowledge as to the optimal values of hold-up and concentration at the start and end of the cycle; it is, in fact, the function of the algorithm to compute these values. To determine the optimum starting values and the optimum profiles the approach was as follows: With regard to, say, volume, the tank hold-up response is governed by the differential equation which relates the rate of change of hold-up, dV/dt , and the inflow and outflow rates, F_0 and F_1 , respectively; i.e.

$$dV/dt = F_0 - F_1 \quad (5.1)$$

In the solution procedure F_0 is fixed and F_1 is initialized as a constant equal to the mean daily inflow rate, \bar{F}_0 ; with the starting conditions such that the daily inflow equals the daily outflow, a necessary condition in the initial solution is that the tank hold-up be the same at the beginning and end of the cycle. This value may be determined by using an iterative procedure, as follows:

An initial value for tank hold-up at the start of the cycle is *specified*. From integration of Eq. (5.1) the hold-up at the end of the cycle is determined. This value is used as the new starting value and the integration is repeated to give yet another starting value, and so on.

It was found that this procedure converged rapidly to give a value of hold-up equal at the start and end of the cycle.*

In the subsequent iterative optimization procedure a necessary requirement is that the hold-up at the beginning and end of the cycle should be the same after each adjustment to the outflow profile, but not necessarily equal to the initial values. This is ensured if, in making each incremental change to the outflow rate over an "improvement" interval, the remainder of the profile is adjusted slightly so that the mean daily outflow rate remains constant and equal to the mean daily inflow rate. Thus, in the initial algorithm, (1) a starting value for the hold-up at the beginning and end of the cycle was obtained from a material balance on flow and (2) thereafter a material balance was maintained throughout the iterative procedure. It is now necessary to examine these two conditions when the algorithm is applied in an on-going control strategy where, in the iterative procedure, the value of the tank hold-up at the start of the cycle is fixed by the *actual* tank hold-up at that time.

When utilizing the equalization algorithm in the control strategy it will now be shown that it is essential that the second condition of specifying maintenance of a material balance must *not* be preserved. Consider a hypothesized case where, at 0h00, the outflow rate is to be set, and the tank hold-up at that time, V_1 , is, for some reason, much *lower* than the optimum value indicated by the equalization algorithm (call this optimum value V_{opt}). Assume further that, in all future cycles, the actual daily inputs are identical to the expected inputs for each cycle. In this situation the action

* This behaviour is a fortuitous result of the form of the differential equation and the functions involved; without this behaviour an alternative method would have been required.

of the strategy should be to "force" the tank in a direction such that the hold-up at corresponding times in future cycles becomes equal to V_{opt} i.e. the tank should move towards optimum performance. This is possible only if material balance principles over the ensuing 24 hour period are *not* obeyed:

If a material balance is maintained and the material leaving the tank equals that entering then, at the end of the cycle, the hold-up, V_2 , will equal V_1 and optimal utilization of the tank volume will not be achieved as the hold-up does not tend to the optimal value, V_{opt} . Optimal equalization can only be attained if some of the day's flow is retained in the tank so that V_2 tends to V_{opt} , i.e. over the day the amount of flow leaving the tank must be less than the amount entering the tank. This behaviour will continue until the hold-up attains the optimal value, and thereafter a material balance will again be evident.

Having described the mechanism for making individual changes to the outflow rate profile at an "improvement" interval it is now possible to outline in detail how the equalization algorithm is incorporated in the control strategy.

2.2 Procedure for Utilizing Equalization Algorithm in Control Strategy

At the beginning of each *control* interval the equalization algorithm is utilized to determine the optimal tank outflow rate for the control interval in question. For the purpose of illustrating the procedure it is assumed that (1) the *expected* influent flow rate and concentration patterns for the ensuing 24 hour cycle is specified, and (2) the *actual* tank hold-up at the beginning of the control interval has been measured. The objective is, using the input profiles and the hold-up, to determine the outflow profile *over the next 24 hours* that will minimize the equalization error;

once this profile is achieved the outflow rate for the *control* interval is set to the value for the corresponding interval in the optimal algorithm solution. At the end of the control interval the procedure is repeated; new expected 24-hour input patterns are determined and the starting value of the hold-up is the *actual* value observed at the end of the control interval i.e. the start of the next interval.

The iterative optimization procedure utilizes the Fast Convergence Approach outlined in Section 3.3.2, Chapter 3. The procedure as applied at the start of a control interval is now set out in detail.

Step 1 : Determine the expected influent flow rate and concentration patterns for the ensuing 24 hour cycle and measure the actual tank hold-up. Set the tank outflow rate profile equal to the optimum determined from the previous application of the algorithm.* The outflow rate profile is made up of N constant portions, each spanning an interval of $(24/N)$ hours, with $n = 1, 2, \dots, N$ being the interval numbers, and Interval 1 corresponding to the control interval under consideration.

Under the expected influent flow and load patterns the associated volume and effluent mass loading profiles are calculated. From the effluent profiles and the volume profile a value for the error expression is calculated.

Step 2 : To evaluate the effects of individual changes at each interval in the outflow rate profile, commence with the first interval ($n = 1$).

* In the absence of any information in this regard the tank outflow rate profile is taken as constant and equal to the mean expected inflow rate for the ensuing 24 hour cycle.

Step 3 : Select the direction of change (increase or decrease) to the outflow rate over the interval as the same as the change made at this interval during the previous cycle (where the interval is being considered for the first time the change may be made in either direction).

Step 4 : Change the outflow rate over the interval by incremental amount, DELTA,* in the selected direction. Calculate the new value of the error associated with the new profile.

Step 5 : Compare the new value of the error with that for the previous profile.

- (i) If the new value of the error is smaller than the error for the previous profile then "accept" the new profile. Go to Step 6 to consider the next interval in the cycle.
- (ii) If the value of the error is larger than or equal to that for the previous profile then reject the possible change, and reverse the direction in which a change in flow rate was made. Return to Step 4.
- (iii) If a change to the profile has been imposed in both directions, and neither has led to an improved error value, then retain the old profile and go to Step 6, to consider the next interval.

Step 6 : If the value of n , the interval being considered, is equal to N , the last interval in the 24 hour cycle, then the cycle of changes has been completed. Go to Step 7.

*

Selection of the magnitude of DELTA is discussed when the requirements for the practical implementation of the strategy is considered.

Otherwise increment the value of the interval number, n , by 1, so that the next interval can be considered, and return to Step 3.

Step 7 : When each of the N intervals has been considered, two possibilities exist:

- (i) At least one change to the outflow profile during the cycle has been "accepted", resulting in an improvement in the error value. In this case further improvements may be possible; repeat the cycle by returning to Step 2.
- (ii) If no change at any of the N intervals has been "accepted" then the tank outflow rate profile cannot be further improved. Set the actual outflow rate from the equalization tank equal to that predicted for interval $n = 1$.

The step by step procedure presented above is carried out at the beginning of each control interval to determine the optimal tank outflow rate for the interval. At any time the optimal outflow, hold-up and concentration profiles predicted for the future 24 hour cycle are based on the *expected* input profiles. In real-time operation it is unlikely that the actual inputs will correspond exactly to the expected inputs; therefore, at the end of a control interval in real-time it is also unlikely that the actual tank hold-up and concentration will equal the values that were predicted by the equalization algorithm for that time when the algorithm was utilized at the start of the interval. The approach to the problem of providing near-optimal performance of the equalization facility on a continuous basis is as follows:

Provided the method for determining the expected influent patterns is reasonably accurate, and provided the length of the control intervals is not too large, the differences between (1) the actual tank hold-up (and concentration)

at the end of a control interval and (2) the values that were predicted by the algorithm at the start of that control interval will be small. By repeating these optimization calculations for the full 24-hour cycle ahead at regular intervals using the actual hold-up and concentration values as the initial values in the algorithm, and then setting the outflow rate for only a short interval, operation of the tank should be maintained at close to the optimum.

It is readily apparent that this procedure by no means supplies a complete control strategy; for example, what happens if the actual inflow is substantially less than the expected inflow at a time when the tank hold-up is close to the lower allowable limit? To account for such behaviour requires some form of "emergency" control to be included in the continuous procedure. The requirements for such a procedure will depend largely on the nature of the particular equalization facility and are discussed in more detail later.

3. PREDICTION OF INFLUENT FLOW RATE AND CONCENTRATION PROFILES

Prediction, at regular intervals, of influent flow rate and concentration profiles for the ensuing 24-hour cycle is required by the control strategy. The method of prediction, however, will depend on the physical means available to implement the control strategy. Hence, it is necessary to identify the requirements for practical implementation.

In Chapter 1 it was stated that the objective in developing the control strategy for the optimal operation of an equalization facility was to provide a simple, low-cost alternative to in-plant control. An obvious corollary therefore, is that the practical requirements for implementation of the strategy should be as simple as possible. A microprocessor-based control strategy has been selected because this provides, at low cost, the computational

facilities required for simultaneous flow and load equalization and, with reliable operation. Keeping the requirements for implementation of the control strategy as simple as possible involves identifying the minimum amount of information that must be passed between the microprocessor and the equalization facility in order to apply the strategy i.e. it is necessary to identify a scheme which involves

- a minimum number of measurements, and
- measurements which are easily made in practice using readily available simple instrumentation.

Using this approach, the following requirements for implementation of the strategy may be identified:

- (1) It has been assumed that the variable on which control action is to be taken in the operation of an equalization facility is the outflow rate from the equalization tank. Therefore, a necessary requirement in an equalization installation will be the facility to measure the outflow rate and to transfer this measurement to the microprocessor. Typically, a flow-measuring flume will be incorporated immediately downstream of the tank. In an existing installation where flow equalization is the objective, the form of flow control would, most likely, be of the feed-back type; the desired flow rate would be specified as a setpoint, and according to whether the flow rate in the flume is either too high or too low, the outlet from the tank will be closed or opened. In a new facility the microprocessor can take the place of the flow controller; by measuring the depth of flow in the flume, and knowing the flow characteristics of the flume, the microprocessor can control the movement of the outlet from the tank and thereby take the place of the flow controller as a part of its function.
- (2) Incorporation of the equalization algorithm in a control strategy also requires information concerning the liquid level in the tank at any instant. Therefore, some form of level measurement must be provided, with the facility to be able to transfer the measurement to the microprocessor.

Measurement of (1) the *tank outflow rate* and (2) the *liquid level* in the tank are the only two physical parameters necessary to define the flow and volume conditions fully. *No influent flow rate* measurements are necessary; having the facility to measure outflow and the tank liquid level at the beginning and the end of a control interval provides the information required to calculate the *mean* influent flow rate over the control interval. In the application of the equalization algorithm under fixed 24-hour inputs of flow and load (Chapter 4) the "smoothed" influent flow rate profiles consisted of a series of point values of flow. However, in practice, where there are rapid random variations in flow rate about a mean trend value, point values of flow rate have little meaning; of more importance is the mean influent flow rate over an interval. Therefore, provided the length of the control interval utilized by the strategy can be suitably selected, there is no need to be able to measure actual influent flow rates; the necessary information can be computed through measuring outflow rates and monitoring changes in liquid level. The above discussion has been related to the measurement of flow rates. Optimal equalization of both flow and load would also require continuous monitoring of the influent concentration. However, this requires equipment which is both complex and expensive. This would nullify, to a degree, the objective of developing a low-cost, simple alternative to in-plant control. It is rather envisaged that information regarding the influent concentration should be stored in the microprocessor and updated as and when information is available. While this approach may be regarded as a shortcoming in the procedure, it will be shown later that it is, in fact, more important to have accurate influent flow rate data than *concentration* data. Briefly, flow and *load* are being equalized, not flow and *concentration*; as load is calculated by the product of flow rate and concentration, the equalization procedure is less sensitive to discrepancies between actual and expected influent concentration values than it is to the corresponding flow rate discrepancies.

Having identified the requirements for implementation of the strategy it is now possible to discuss the methods used for predicting 24-hour influent flow rate and concentration patterns.

3.1 Historical Influent Flow Rate and Concentration Profiles

In Fig. 2.5, Chapter 2, influent flow and load patterns measured over a period of one week at the Goudkoppies Sewage Works, Johannesburg, illustrated the following features:

- (1) From Monday to Friday the diurnal flow pattern is repeated, with relatively small variations. A similar trend is exhibited by the load pattern.
- (2) The *form* of the flow and load patterns on Saturday and Sunday, while similar to each other, differ considerably from those observed on weekdays.
- (3) The *mean* daily influent flow and load rates during the weekend are appreciably lower than the corresponding mean values during the week.
- (4) The influent patterns exhibit rapid, random variations about the average diurnal influent patterns.

The factors causing the above behaviour were dealt with in Chapter 2; the purpose here is to utilize this information to determine a method whereby satisfactory estimates of the influent flow rate and concentrations profiles for an ensuing 24-hour cycle may be made at any instant. These expected influent profiles are to be used by the equalization algorithm in the control strategy.

The approach taken in this investigation is that the estimates of the expected influent patterns for a 24-hour cycle should be based primarily on historical inflow and concentration data. This approach seemed reasonable as the diurnal influent patterns are generally repeated, with only small variations, from day to day. Changes in the form of the influent patterns and the mean daily influent values occur only slowly in a cyclic fashion over the year

as a result of seasonal effects (or where physical changes occur in the collection system); it will be shown that appropriate procedures can be included in the strategy so that these changes can be suitably incorporated automatically on a continuous basis.

3.1.1 Historical influent flow rate profiles

An historical influent flow rate profile for the 24-hour cycle may be obtained from an analysis of data collected over a period at the particular plant. Averaging point values of flow rate at, say, half-hourly intervals over the day, and drawing a "smoothed" curve through the data points, will yield a continuous curve reflecting the average daily inflow rate profile for that period.

It was stated earlier in Section 3.1 that in practice, where there are rapid random variations in flow rate about a mean trend value, point values of flow rate have little meaning; of more importance is the mean inflow rate over an interval of larger duration than the period of these rapid variations. For this reason, the historical influent flow-rate profile used by the equalization algorithm is made up of a number of values, each reflecting the mean inflow rate over a particular interval in the 24-hour cycle. With regard to the length of these intervals it was found to be most convenient if it was taken as the same as the length of the control intervals (and "improvement" intervals). This step function historical influent flow rate profile is obtained from analysis of the first historical profile consisting of averaged point values, taking into account the number of intervals over the day.

In practice, through *measuring* the outflow rate and the change in tank level over a control interval, the *actual* mean influent flow rate over the control interval is determined.* In this fashion,

* There is no restriction to measuring mean inflow rates over a control interval; any length of interval could be selected. However, for computational reasons, it was most convenient if the lengths of the control intervals, "improvement" intervals, and the inflow rate profile intervals are taken as equal.

each day a set of actual mean influent flow rates, one rate for each control interval, is generated. These measurements afford a means by which seasonal (or other) changes in the average daily inflow rate profile can be incorporated to maintain an accurate running average of the daily influent flow rate profile. This may be achieved as follows:

For any interval in the 24-hour cycle there is an historical value of the mean influent flow rate for that interval stored in the computer memory for use by the equalization algorithm; this value most probably will differ slightly from the actual mean influent flow rate measured over that interval. This difference could reflect (1) the random variation about the average influent pattern, and/or (2) a change in the form of the influent pattern. It was found that if the historical value for that interval is updated by taking the "new" historical value to be equal to the sum of, say, 95 percent of the existing historical value and 5 percent of the actual value, the historical 24-hour pattern reflected the mean diurnal influent pattern on a continuous basis, i.e. a running average influent 24-hour pattern was stored in the computer memory. In this way, the effects of seasonal changes in the influent pattern were automatically incorporated in the control strategy. An additional benefit of this approach was that the 24-hour influent pattern used on initiating the control strategy need not be particularly accurate. After a few days, the initial pattern will be updated to reflect the actual average influent pattern.

In the initial development of the control strategy a single 24-hour historical influent flow rate profile was stored in the microprocessor memory for use by the equalization algorithm. At a later stage it was found necessary to utilize two different 24-hour historical influent patterns - one for the weekdays, and one for the weekend days - in order to overcome problems in the major transition experienced from weekday to weekend. This feature will be dis-

cussed in more detail when the application of the control strategy on a continuous basis is demonstrated.

3.1.2 Historical Influent Concentration Profiles

The historical influent concentration profiles may be obtained in a similar manner to that used for the influent flow rate profile - using data measured over a period at the plant, and averaging point values at intervals over the day, and then drawing a "smoothed" curve through the resulting data points to obtain an average influent concentration profile for the 24-hour cycle. This historical influent concentration data is stored in the micro-processor memory for use by the equalization algorithm as follows:

Point values of concentration at times corresponding to the beginning of each "improvement" interval over the 24-hour cycle (i.e. the end of the previous interval) are stored. For example, where the 24-hour cycle is divided into 48 half-hourly "improvement" intervals, the historical influent concentration data consists of 49 values, with the first and last values being equal i.e. the values at 00h00 and 24h00. In the computation of the tank concentration response it is assumed that the influent concentration over an "improvement" interval varies linearly between the values at the start and end of interval.

If equipment is available for monitoring influent concentration on a continuous basis, then historical concentration data stored in the microprocessor memory could be updated in the same manner as that used for updating the flow rate data. However, in this investigation, it is assumed that there will not be continuous monitoring of concentration. In this case, due to the partial insensitivity of the equalization procedure to concentration fluctuations (discussed earlier), it most probably will be sufficient if the concentration data is updated only at intervals of, say, 3 months.

3.2 Accounting for Instantaneous Differences between Actual and Historical Influent Values

At the beginning of a control interval during application of the control strategy the expected influent flow rate and concentration profiles for the ensuing 24-hour cycle may be obtained from the historical patterns stored in the computer memory. The actual inflow rate and concentration over the previous interval are unlikely to have been equal to the corresponding values from the historical pattern. Projecting this into the future, if, say, the actual inflow rate over the previous interval was greater than the corresponding historical value, then it is likely that this behaviour will persist and the inflow rate over the next control interval, and perhaps subsequent intervals, will also be greater than the historical values for the corresponding intervals. That is, the expected influent patterns for the subsequent intervals will depend not only on the historical values for those intervals, but also on the actual immediate past behaviour relative to the immediate past historical values. It was therefore decided that the *expected* influent profiles for the ensuing 24-hour cycle to be used by the equalization algorithm should be based on the *historical* profiles *together with an adjustment* to take into account the immediate past behaviour. The detailed mechanisms for making the adjustments are set out below.

3.2.1 Adjustment to Influent Flow Rate Profile

In simulations where the historical influent flow rate profile constituted the sole source for determining the expected influent pattern, differences between the actual and historical influent flow rates did not pose a problem provided the difference was small at the times when the tank hold-up was close to the upper or lower limit. However, it was found that when either (1) the actual inflow rate substantially exceeded the historical value and the hold-up was close to the upper limit, or (2) the actual inflow rate was substantially less than the historical value and the tank hold-up was close to the lower limit, situations of overflow and underflow (emptying),

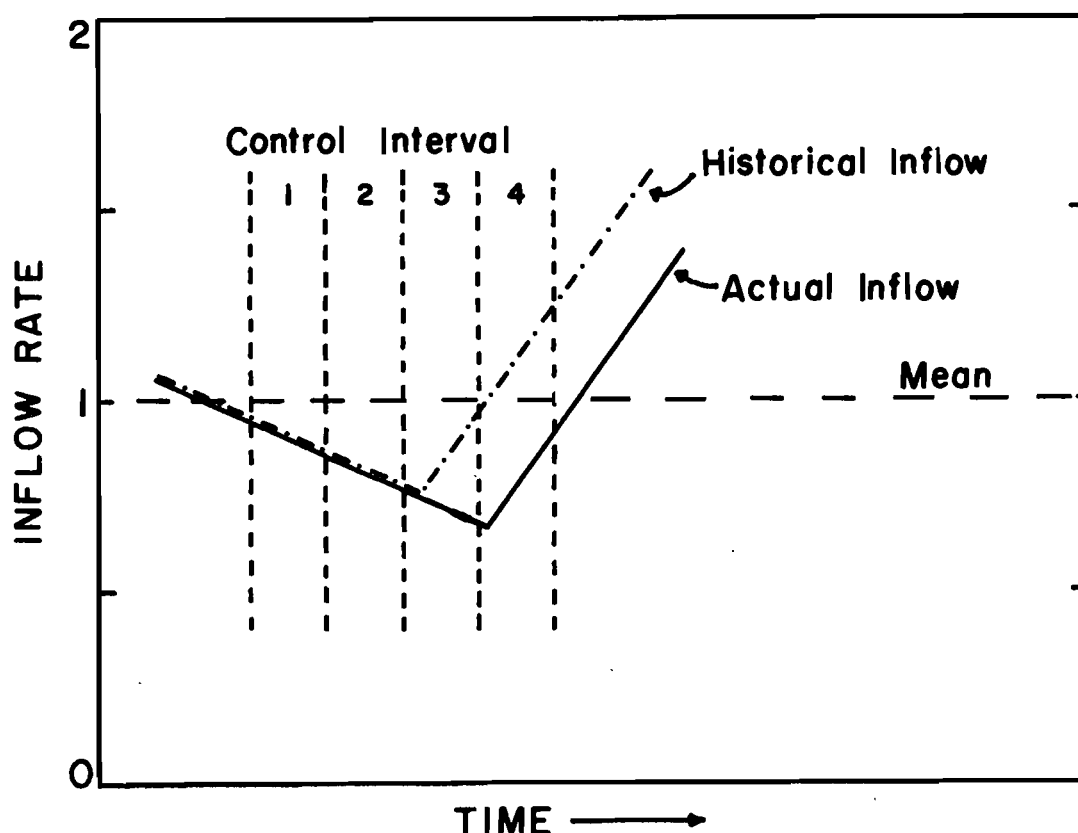


Fig. 5.1 Illustration of the effect of difference between actual and historical influent flow rates.

respectively, were encountered. These effects are perhaps best illustrated by an example: Fig. 5.1 illustrates a situation where, after a period of minimum inflow, there is a lag in the actual increase in influent flow rate compared to that given by the historical pattern. From the tank hold-up profiles in Chapter 4, it is apparent that when the outflow rate is equalized to maintain a value near the daily mean value, the tank hold-up will be close to its minimum value when the inflow rate is a minimum; the hold-up passes through its minimum when the inflow rate increases to the mean. Over control intervals 1 and 2, the control strategy that determines the effluent flow rate exclusively on the historical pattern, will specify an outflow rate which remains close to the mean. At control interval 3, although the tank hold-up may be close to the lower limit, the control strategy based only on historical flows will not reduce the outflow rate because a rapid increase in

the influent flow rate is expected historically. If, at the end of control interval 3, the tank hold-up is at the lower limit, the control strategy still will not reduce the outflow rate below the mean (in order to avoid underflow) because the outflow rate is based on an expected historical inflow rate in excess of the mean. However, if the actual inflow rate is still less than the outflow rate (near to the mean) over interval 4, the tank hold-up actually will drop below the allowable limit. The severity of this problem will increase as the duration of the lag increases. To prevent this type of situation from developing, the *expected* influent flow rate pattern for a 24-hour cycle predicted at the beginning of a control interval should be based on the *historical* influent flow rate pattern, together with an *adjustment* to account for the difference between the actual and historical influent flow rates prior to the prediction. The adjustment is determined as follows:

At the beginning of a control interval, when the influent flow rate profile for the ensuing 24-hour cycle must be predicted, the actual mean inflow rate for the previous interval is calculated in order to update the historical data. The difference between the actual and the historical influent flow rates for the previous interval, ΔF_p , is given by

$$\Delta F_p = F_{\text{act},p} - F_{\text{hist},p} \quad (5.2)$$

where

$F_{\text{act},p}$ = mean actual inflow rate over previous interval

$F_{\text{hist},p}$ = mean historical inflow rate over previous interval

The historical influent flow rate profile for the ensuing 24-hour cycle is made up of N historical influent flow rate values, one for each of the N "improvement" intervals. The expected inflow rate profile (to be used by the equalization

algorithm) is determined by adjusting each of the N historical values as follows: The historical value for the *first* interval in the ensuing 24-hours is adjusted by an amount D_1 , i.e.

$$F_{\text{exp},1} = F_{\text{hist},1} + D_1 \quad (5.3)$$

Thereafter the historical values for the subsequent intervals ($j = 2, 3, \dots, N$) are each adjusted by progressively decreasing amounts, with the magnitude of the adjustment at an interval being equal to some fraction of the adjustment at the interval before, i.e.

$$D_j = a D_{j-1} \quad \text{for } j = 2, 3, \dots, N \quad (5.4)$$

so that

$$\begin{aligned} F_{\text{exp},j} &= F_{\text{hist},j} + D_j \\ &= F_{\text{hist},j} + a D_{j-1} \end{aligned} \quad (5.5)$$

where

$F_{\text{exp},j}$ = expected mean inflow rate over j -th interval

$F_{\text{hist},j}$ = historical mean inflow rate over j -th interval

a = a factor ($a < 1$)

For example, the expected mean inflow rate over the second interval in the ensuing 24-hour cycle is given by

$$\begin{aligned} F_{\text{exp},2} &= F_{\text{hist},2} + D_2 \\ &= F_{\text{hist},2} + a D_1 \end{aligned} \quad (5.6)$$

and so on, until for the last interval in the ensuing cycle, N ,

$$\begin{aligned} F_{\text{exp},N} &= F_{\text{hist},N} + D_N \\ &= F_{\text{hist},N} + a D_{N-1} \end{aligned} \quad (5.7)$$

In this manner the expected influent flow rate profile for the ensuing 24-hour cycle is determined. It is now necessary to explain how the adjustment at the first interval, D_1 , is calculated.

By trial and error it was found that good results were obtained if D_1 is given by the weighted sum of the ΔF values calculated from Eq. (5.2) for the preceding two control intervals, ΔF_p and ΔF_{p-1} respectively, as follows

$$\begin{aligned} D_1 &= b\Delta F_{p-1} + (1-b)\Delta F_p \\ &= b(F_{\text{act},p-1} - F_{\text{hist},p-1}) \\ &\quad + (1-b)(F_{\text{act},p} - F_{\text{hist},p}) \end{aligned} \quad (5.8)$$

where

$$b = \text{a weighting factor (} 0 < b < 0,5 \text{)}$$

In this way, if the ΔF values are due to random fluctuations about the historical values (say ΔF_{p-1} is negative and ΔF_p is positive, or *vice versa*) then the adjustments to the historical values will be small; however, if both are positive or both negative, indicating that the trend in the difference between the actual and historical profiles is persisting, the adjustment is larger.

3.2.2 Adjustment to Influent Concentration Profile

If continuous monitoring of influent concentration is included in the equalization installation, then the expected influent concentration profiles for a 24-hour cycle can be obtained by making an adjustment to the historical concentration profile in a manner similar to that for flow rate. Where monitoring of concentration is not included, a different method for adjusting the historical profile is required. One method is to assume that the mass of material entering the equalization tank over a certain interval is the same from day to day. If the flow rate over that interval, say, exceeds the historical value then it would be reasonable,

perhaps, to assume that the concentration will be lower than the historical value. However, because the historical influent concentration will only approximate the actual values, it was deemed that the added complexity introduced by adjusting the approximate profile is not warranted. Therefore, in this study, where continuous monitoring of concentration is excluded, the expected influent concentration profile for a 24-hour cycle is based exclusively on the historical values stored in the computer memory.

4. COMPUTER PROGRAM FOR SIMULATION OF CONTROLLED EQUALIZATION TANK RESPONSE

The final version of the control strategy incorporating the equalization algorithm was developed over a period of time. In order to be able to assess each version of the control strategy, a computer program was used to simulate the real-time controlled response of an equalization installation under inputs of flow and load observed at full-scale WWTPs. For a program to simulate an actual control scheme, two models are needed:

- (1) A simulation of the actual tank, with *real* inflow and concentration signals, which will calculate by integration (with small integration step lengths) what the actual tank concentration and hold-up is over the period of the simulation. Information regarding the tank outflow rate is obtained from (2), below.
- (2) A control strategy. This will also simulate a tank for its internal use, but using the *expected* influent flow rate and concentration profiles as well as the actual tank hold-ups (from (1) above), and establish a setting for the outflow rate at intervals.

In a real system (1) above will relate to the actual plant whereas (2) above will be located in a microprocessor. For this reason, it is convenient to separate the two components in the simulation program.

Initially a general ASCII FORTRAN program was written to simulate controlled operation of either (1) an in-line equalization tank, or (2) a side-line equalization tank with flow division either by "topping" or by "splitting". The program is listed in Appendix C, together with detailed instructions for its use. Two problems were encountered in the use of this general program; namely (1) the computer storage requirements for the program are relatively large, and (2) simulation of the controlled equalization facility for, say, a two-day period (used in this study) requires long execution times. In practice, it can be expected that a limit would be imposed on the allowable storage capacity, depending on the microprocessor used in the implementation. Furthermore, it would be desirable to minimize the amount of computation time required to implement the control strategy. For these reasons an effort was made to reduce both the storage requirement and the execution time of the simulation program.

- (1) Storage Requirements. The storage requirements for the computer program in general will depend primarily on (1) the number of arrays of data utilized in the calculation procedure, and (2) the number of elements stored in each array. The number of arrays may be reduced by considering a less generalized problem. For example, fewer arrays would be required for a program simulating only an in-line tank than would be required in a more general program for both an in-line or a side-line tank. In the problem discussed above the number of elements in the majority of the arrays is dependent on the length of the numerical integration step used in the simulation of the tank response *by the equalization algorithm*. In the general program the equations governing the response of the equalization tank are approximated by finite difference, as was the case in the program for the equalization algorithm in Chapter 3; short integration step lengths of about 5 minutes are required in order to limit the magnitude of the errors, resulting in arrays containing as many as 289 values. In the case of simulation of the

real tank it is necessary to use short integration steps in view of the rapid, random variations in the influent flow rate and concentration data used in the simulations. However, where the equalization algorithm simulates the tank response for its own use, the profiles used in the computations do not exhibit rapid variations over the duration of an "improvement" interval. Therefore, providing a suitable integration technique is used, it is no longer necessary to subdivide the "improvement" intervals into a large number of short simulation intervals; in fact, providing the "improvement" interval is not too long ($< 0,5$ h), it is not necessary to subdivide the interval at all. Using this approach the number of elements stored in the arrays of the equalization algorithm can be reduced substantially.

- (2) Program Execution Time. It was found that the program execution time required for simulation of the controlled equalization tank is primarily dependent on the lengths of the integration steps utilized by the *algorithm*. This is reasonable to expect because the large portion of the calculation in the simulation involves optimization of the out-flow rate profile at the beginning of each control interval; a relatively small amount of calculation is required to simulate the real tank response over the control interval. The total execution time increases almost linearly as the length of the integration step in the equalization algorithm is decreased. Therefore, by following the method used to decrease the storage requirements through increasing the length of the integration step in the simulation of the tank by the algorithm, a substantial decrease in program execution time may be realized.

A second ASCII FORTRAN computer program was written to simulate the controlled operation of an equalization tank with the objective of minimizing both the program storage requirement and the execution time. As a part of the requirement to reduce the storage through

reducing the number of arrays of data, the program was written for the case of an in-line equalization tank only. This decision was taken primarily because the opportunity existed to implement the control strategy on an in-line tank at the Goudkoppies Sewage Works. In addition, it was deemed unnecessary to use a third program for the side-line case as only a few simulations were required and these could be performed using the first program. A listing of the program for the in-line case, together with detailed instructions for its use, is presented in Appendix C.

In the program the "improvement" intervals in the equalization algorithm are not subdivided into a number of shorter simulation intervals; it was found that provided the length of the intervals is not greater than 30 minutes, the Runge-Kutta integration method can be used successfully to compute the tank response. Initially the fourth order method was used; however, second order Runge-Kutta integration gave almost identical results, and was selected for its smaller computation requirements.

For the purpose of comparison and graphical evaluation of the results obtained from application of the equalization control strategy in simulation, a plotting program utilizing the CALCOMP package was written; a listing of this program, together with instructions for its use, is also presented in Appendix C. The program is used to present the results from the simulation of a two day period of controlled equalization tank operation.

At this point one comment should be made concerning the results from simulation by application of the control strategy; the effect of updating the historical influent flow rate patterns was not tested in the simulations. The controlled response of the equalization facility was generally only performed for a two day period because simulations for longer periods required prohibitively long computation times. A period of two days allows each historical value of flow rate to be updated twice, which is not enough to be

able to evaluate the suitability of the method used. Therefore, evaluation of the method of updating could only be obtained from the practical implementation of the strategy after a period of weeks or months. This small feature does not detract from the importance of the simulations in evaluating the control strategy.

5. APPLICATIONS OF CONTROL STRATEGY

In Chapter 6 the simulation program for the controlled response of an equalization facility will be used to evaluate in detail (1) the efficacy of the control strategy, (2) the effect on performance of various parameters such as equalization tank size and the weighting factors in the error expression, and (3) the suitability of in-line as opposed to side-line equalization tanks. In order to introduce and illustrate the strategy one particular situation only will be considered here, where the configuration and tank size are specified, and equal weight is given to flow and to load equalization, as follows:

- (1) An in-line equalization tank with a mean retention time of 5,5 hours is selected i.e. the tank volume is 23 percent of the average daily influent flow, which approximately corresponds to the tank size normally encountered in practice.
- (2) Upper and lower allowable tank hold-up limits of 95 and 5 percent, respectively, of the maximum hold-up have been selected.
- (3) Control interval lengths of 0,5h are used in the simulation.

The computer program was used to simulate the controlled response of the equalization tank for a two day period under inputs of flow and concentration measured at the Cape Flats Sewage Works. The results of the simulation (produced by the CALCOMP plotting program) are presented in Fig. 5.2, which consists of four sections:

- (1) The uppermost section of the diagram shows the actual influent flow rate to the equalization basin as a solid line,

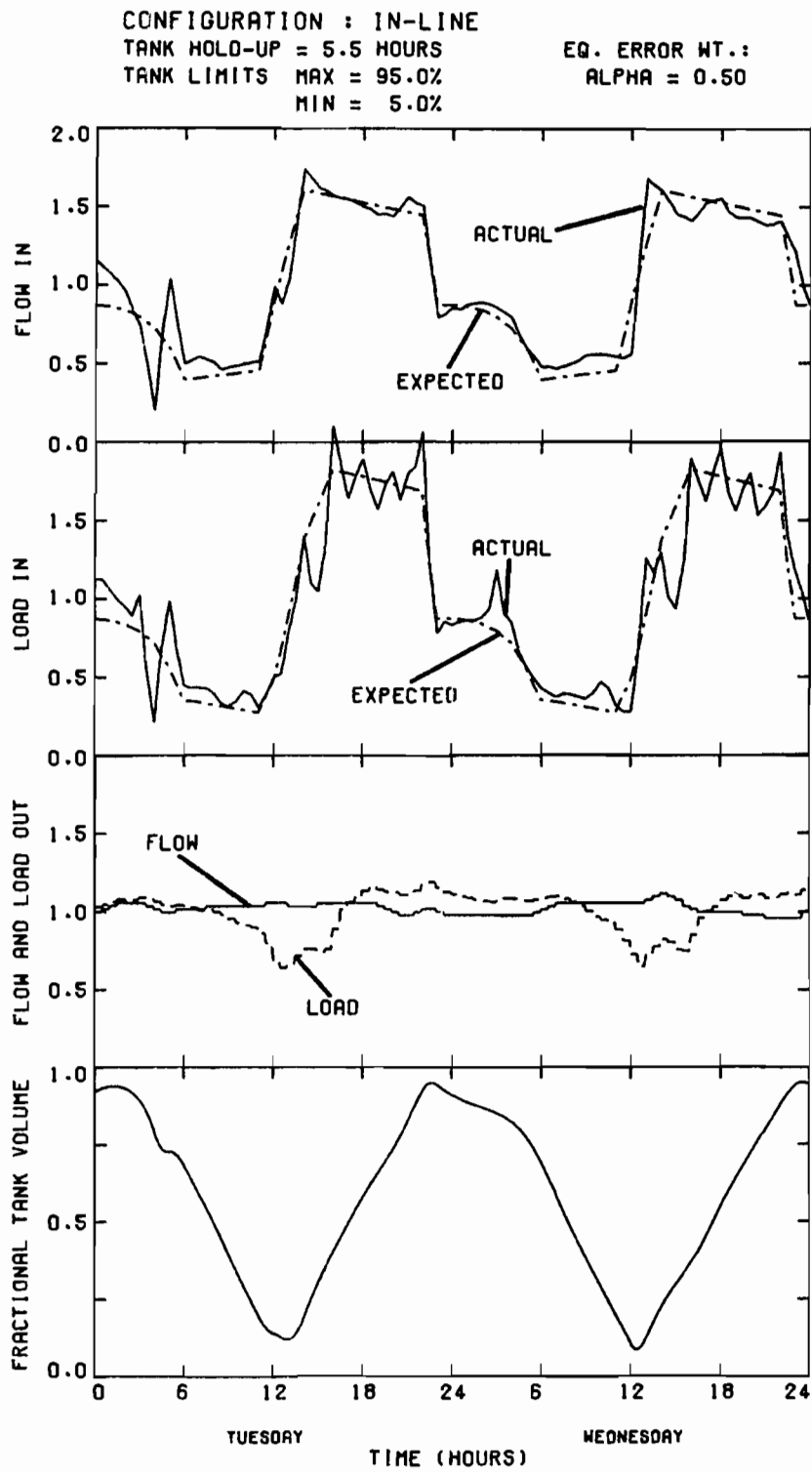


Fig. 5.2 Example of the controlled equalization tank response for a two day period (Cape Flats influent data).

while the historical influent flow rate pattern is shown as a broken line.

- (2) The second section shows the corresponding information for the load; the solid line represents the actual influent load and the broken line the historical influent load rate pattern.
- (3) The third section shows the controlled tank outflow rate as a solid line with small step-changes where adjustments are made, and the associated effluent load rate as a broken line.
- (4) The tank hold-up response over the two day period, as a fraction of the total tank volume, is shown in the lowest section of the diagram.

At the top of Fig. 5.2 information is supplied regarding (1) the equalization configuration, (2) the tank size, (3) the allowable tank hold-up limits, and (4) the value of the equalization error weighting factor, α .

Certain features regarding the results presented in Fig. 5.2 are readily apparent in light of the detailed discussion concerning the application of the equalization algorithm in Chapter 4, and will not be discussed again here; however, certain additional features are worth mentioning:

- (1) The method used for incorporating the equalization algorithm appears to be successful in that the form of both the effluent flow rate and the load rate patterns are very similar to the "ideal" patterns for the same tank size (see Fig. 3.5) obtained under fixed inputs, despite the differences between the actual and historical influent patterns.
- (2) In this example the increase in outflow rate required to sustain the load over the period where both the influent load and hold-up are low is more marked on the Wednesday than Tuesday. This difference is explained by considering the

actual influent flow rate pattern at midday Tuesday; the control strategy has not specified the expected increase in outflow rate because it has taken into account the sudden drop in the actual inflow rate which occurs at 12h00.

Although this action may appear to be oversensitive it is nevertheless required because, at the time when the action is taken, there is no information about the period for which the deviation in flow rate would persist.

- (3) The deviations in the actual influent *load* rate are more marked than those of the flow rate with regard to both (1) the amplitude of the expected pattern, and (2) the deviations of short duration about the trend value. It is of interest to note how (1) the tank acts as a buffer to smooth the load pattern, and (2) despite the peak influent load of 2,10 times the mean, the effluent load rate never exceeds 1,15 times the mean.

Additional features regarding the performance of the control strategy could be discussed here. However, these aspects will be considered in detail in Chapter 6. The purpose of this example is only to introduce the strategy, the format of the results, and briefly to illustrate the approach used in interpreting the results. Before proceeding to the more detailed discussion the problem of accounting for the transition from a weekday to a weekend is considered.

6. INCORPORATION OF WEEK/WEEKEND TRANSITION IN CONTROL STRATEGY

In Section 3.1.1, which dealt with the historical influent flow rate patterns, it was mentioned that problems may be encountered in the transition from a weekday to a weekend when there may be a change in both (1) the *form* of the influent flow and load rate patterns and (2) the *average* daily influent flow and load. The severity of the problem will depend on the magnitude of these changes which, in turn, will depend on the nature of the wastewater collection area;

for example, if the collection was exclusively from commercial districts, then it would be reasonable to assume that weekend wastewater flows and loads would differ appreciably from those on weekdays. The influence on the control strategy performance in the transition from a weekday to a weekend is now tested as follows:

An in-line equalization tank with a mean retention time of 5,5 hours is utilized; this is the same tank size as for the first example in Section 5. Again equal weight is ascribed to flow and to load equalization. Actual influent data collected at the Cape Flats Sewage Works over a Friday/Saturday sequence is used in the simulations.

Fig. 5.3 illustrates the behaviour of the control strategy under the measured inputs of flow and load in transition from a Friday to Saturday. In the simulation the historical daily influent patterns utilized by the equalization algorithm were obtained by averaging available data including both weekdays and weekend days. The difference between the actual Saturday influent patterns, both in form and average value, with the average historical patterns, is shown clearly in the upper two sections of Fig. 5.3. The behaviour of the control strategy is best understood by following the tank effluent flow and load rate profiles from left to right in the Figure while referring to the differences between the actual and historically expected influent patterns; it should be noted that, while the strategy is able to incorporate to some extent differences in flow rate through adjusting the historical flow profile, this is not true with respect to differences in load as continuous monitoring of concentration is not included:

Until Friday midday the effluent flow rate remains almost constant at the mean value. The strategy does not cause the flow rate to increase at about midday in order to sustain the load because there is a lag in the expected rapid increase in influent flow for almost two hours after midday; in fact, it is necessary to slightly decrease the outflow rate in order

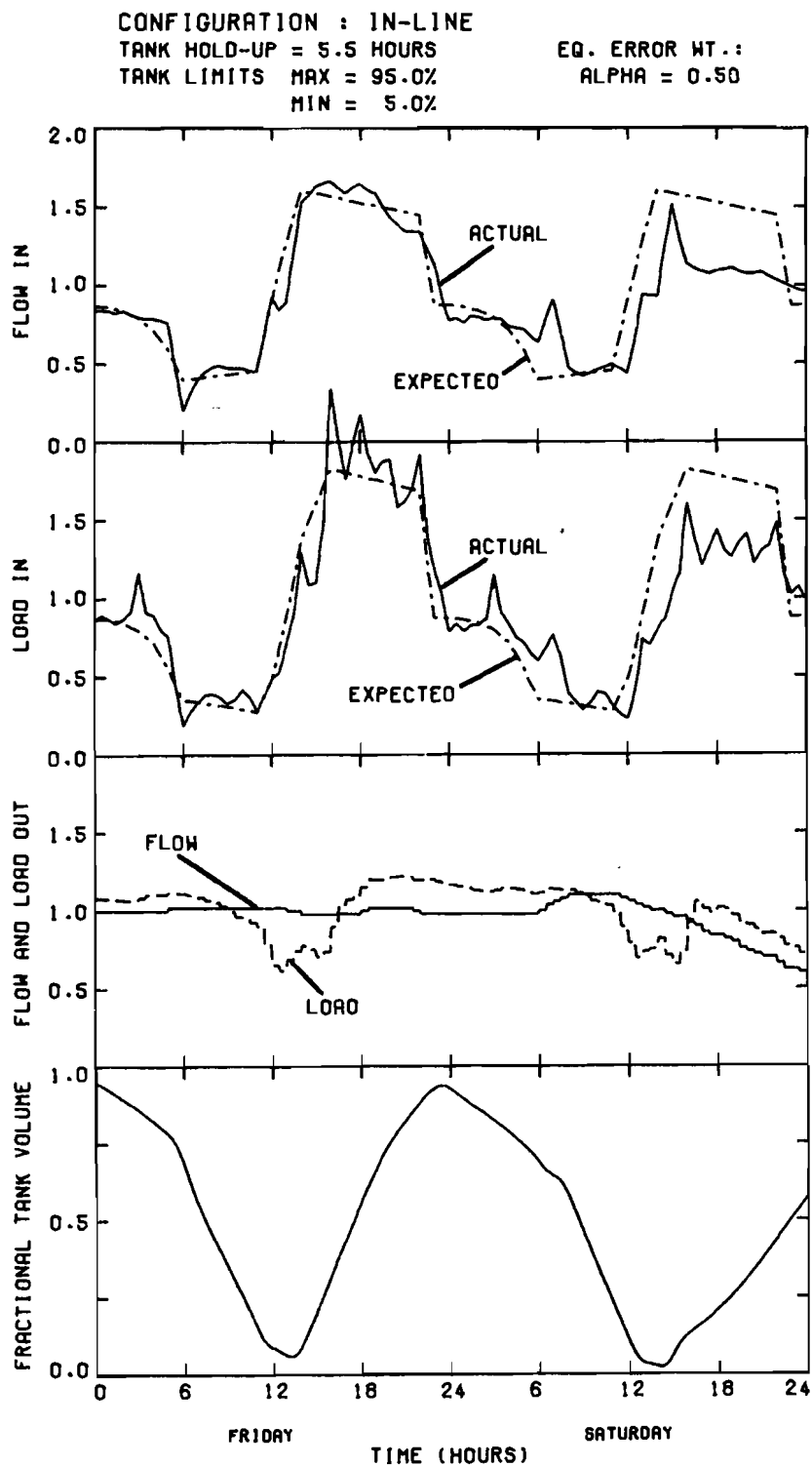


Fig. 5.3 Behaviour of control strategy during a Friday-Saturday sequence when expected daily influent patterns are taken to be the average for the whole week.

to avoid dropping the tank hold-up to less than the specified allowable limit of 5 percent. Between 04h00 and 09h00 on the Saturday the actual inflow exceeds the expected inflow, and in addition, the inflow rate is expected to increase rapidly soon after midday; therefore, action is taken to increase the outflow rate in order to sustain the load over the midday period because no danger is anticipated with regard to emptying the tank. After midday Saturday the behaviour of the strategy becomes inadequate as regards equalizing the flow and load because for the remainder of the day the influent flow and load rates are both substantially lower than the expected values, except for a short period close to midnight. After midday the strategy is forced to continuously decrease the flow rate until, at midnight, the effluent flow and load are only 0,65 and 0,72 of their respective mean values. This is in sharp contrast to the usual weekday situation where the effluent flow and load rates are close to the mean values at midnight; in addition, the tank hold-up at midnight is less than 60 percent, whereas usually the hold-up at midnight is close to the allowable maximum. When extended to the Sunday, noting that the initial tank hold-up is low and that both the influent flow and load on the Sunday are again less than that expected by the strategy, it is evident that the strategy will be forced to reduce the outflow rate even further to avoid emptying the tank.

In an attempt to overcome this behaviour it was decided that where data indicated substantial differences in the influent flow rate and concentration patterns between weekdays and weekends two sets of historical influent patterns should be stored in the computer memory for use by the equalization algorithm; one for the weekday patterns and one for the weekend patterns. By using this approach it would seem reasonable to expect the strategy to deal more adequately with the weekday-weekend transition because from early Friday the strategy already would be able to start making provision for the weekend situation.

From an analysis of data measured at three full-scale plants it was found that, while the weekend *flow* pattern differed substantially from the weekday pattern, there was not a great difference between the corresponding influent concentration patterns. This observation may not be accepted as a generalization; whether or not a distinction is required between weekday and weekend influent concentration patterns may differ from one plant to another. In fact, for certain plants there may not even be a necessity to distinguish between different flow or concentration patterns. In the case considered here it was decided to store in the computer memory three historical influent patterns: (1) a weekday flow pattern, (2) a weekend day flow pattern, and (3) a single concentration pattern.

Figure 5.4 shows the resultant effect on the behaviour of the control strategy for the same Friday-Saturday sequence where a distinction is made between the historically expected weekday and weekend influent flow rate patterns. The following features are apparent in the Figure:

- (1) The marked difference between the historically expected influent flow and load rate patterns for the weekday and the weekend day is shown in the upper two sections of the Figure.
- (2) From midday Friday periodically the outflow rate is decreased to take account of the anticipated lower weekend flow. However, at midnight Saturday the outflow rate is only reduced to about 0.8 of the mean while the load is at the mean value (cf. Fig. 5.3).
- (3) The feature perhaps most prominent is that the action of the control strategy is to reduce the tank hold-up only to 23 percent despite the lower allowable limit being 5 percent. The results of this action is two-fold: Firstly, by not allowing the tank to almost empty, the additional storage of liquid will allow the outflow rate to be maintained at a reasonable level on the Sunday; and secondly, the increased hold-up allows for improved load equalization - in fact, the minimum Saturday effluent load slightly exceeds that for the Friday.

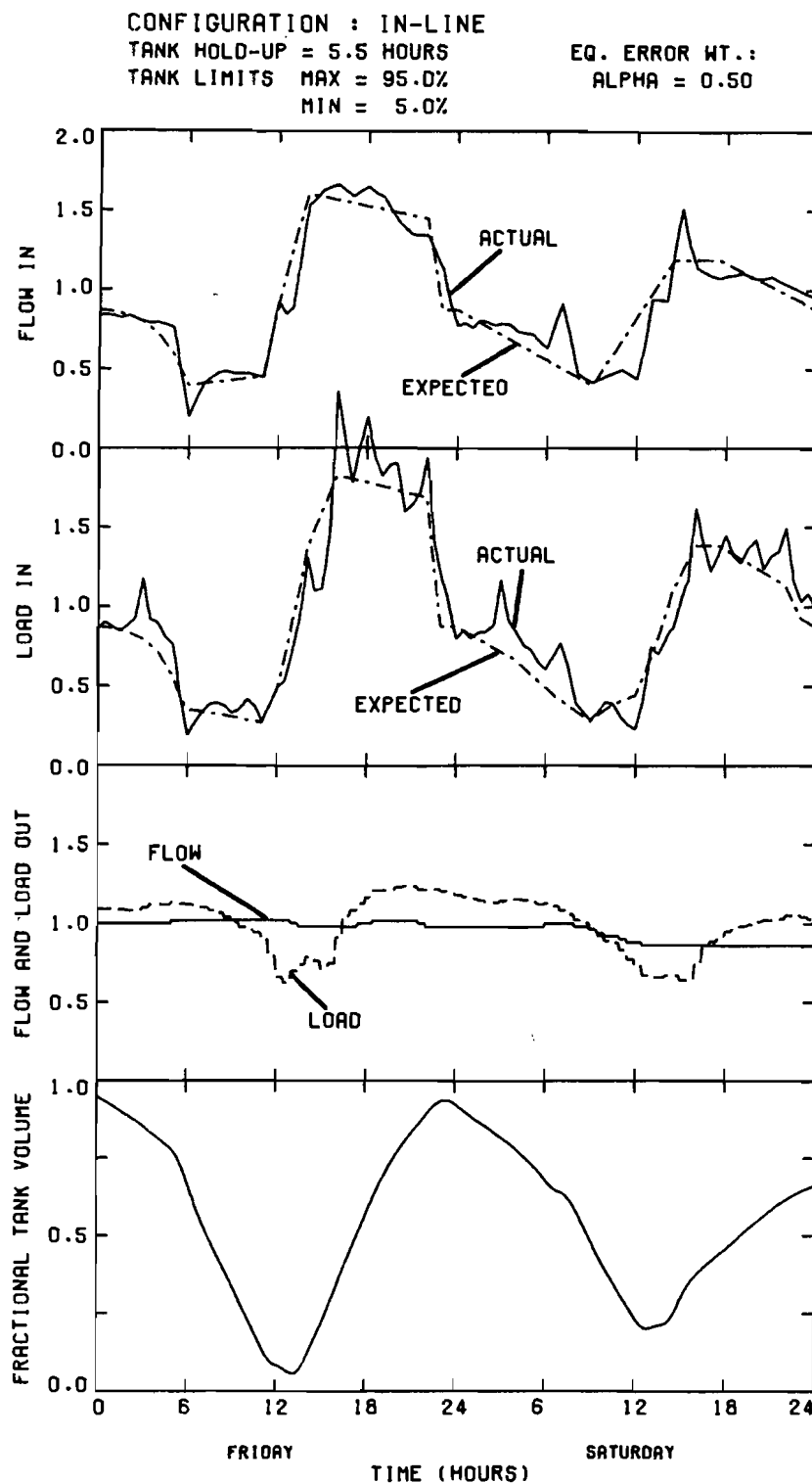


Fig. 5.4 Behaviour of control strategy during a Friday-Saturday sequence when a distinction is made between the weekday and weekend historical influent flow rate patterns.

CHAPTER SIX

APPLICATION OF CONTROL STRATEGY

1. INTRODUCTION

In Chapter 3 an equalization algorithm was developed for the purpose of identifying optimal performance of any given equalization facility under specified invariant 24-hour input patterns of flow rate and concentration, i.e. where the 24-hour cyclic patterns are repeated identically from day to day. In Chapter 4 the principal factors affecting the performance of an equalization facility under invariant daily cyclic input patterns were identified, and evaluated quantitatively, i.e.

- the size of the equalization tank
- the nature of the expected influent flow rate and concentration patterns
- the equalization facility configuration, i.e. in-line or side-line.

In Chapter 5 the equalization algorithm was incorporated, with suitable modifications, in a control strategy with the objective of providing a means to optimally control the performance of an equalization facility on a continuous basis under real-time conditions - conditions that are non-ideal in the sense that both the influent patterns of flow rate and concentration, and the masses of influent flow and load, do not remain constant from day to day. The equalization control strategy was applied in two situations only, to determine whether or not the strategy constitutes a viable means for providing near-optimal operation of an equalization facility. The results of these two applications indicated very positively that the approach has potential. However, before accepting the strategy it is necessary to test it over a range of conditions and situations that can be encountered in practice, under input patterns of flow rate and concentration

actually measured at full-scale WWTP's. The advantages accruing from such tests can be listed as follows:

- The tests will allow evaluation of the applicability of the guide-lines for equalization tank design (proposed on the basis of the analysis under invariant daily cyclic input patterns) under real-time conditions.
- The behaviour of the strategy under storm conditions can be investigated. Such events usually occur at random intervals and consequently are not reflected in the historical data for the average trend pattern of flow to the plant; therefore, it is necessary to inquire into the propensity and efficiency of the strategy to accommodate and minimize the storm effects.
- Emergency control situations can be identified and demonstrated, and counter measures incorporated in the strategy. Situations may arise in which the control strategy based on the equalization algorithm must be superceded by some form of emergency action. A typical situation of this kind is that at a critical time in the daily cycle when the tank hold-up is close to the lower operating limit - the tank outflow rate (specified according to the equalization algorithm) may cause the hold-up to drop below some absolute minimum hold-up limit.* It is necessary for the control strategy to identify this, and other crisis situations, and to bring into operation emergency procedures for accommodating the adverse effects.

By analyzing a number of appropriately selected cases that include the abnormal and critical situations set out above, the response characteristics of the control strategy allows the magnitudes of the problems created by these events to be evaluated, and thereby provide the basis for developing counter-procedures for incorporation in the strategy to minimize or eliminate the adverse effects.

* Such a hold-up limit typically would exist when floating aerators requiring a certain minimum operating depth are provided for mixing of the tank contents.

2. SIMULATIONS OF CONTROL STRATEGY PERFORMANCE

Application of the control strategy in the various tests discussed above requires specification of, *inter alia*, (1) upper and lower allowable or operational tank hold-up limits for use in the equalization algorithm; (2) values for the error expression weighting factors (α , β , and ω) in the equalization algorithm; and (3) the length of the control intervals (which is the same as the length of the adjustment intervals in the equalization algorithm). Selection of the magnitudes of these parameters has been discussed in Chapter 3, and the various factors entering into their selection have been identified. The result of that analysis was to provide a range of possible values which would lead to optimal equalization. The values used in the simulations presented in this Chapter are summarized in Table 6.1; these values are very close to, or identical to those selected in Chapters 3 and 4. However, under real-time operational conditions, the following points are worth noting regarding the choice of these values:

(1) Hold-up limits: The hold-up limits are specified as a percentage of the total tank depth, a practice followed throughout this investigation. Maximum and minimum limits of 95 and 5 percent, respectively, have been selected here for two reasons:

- These values most probably will be satisfactory for a wide range of situations encountered in practice. By choosing the limits close to the extreme values, almost the full capacity of the tank can be utilized while still providing a margin of safety to accommodate differences between the actual and historical inflow profiles over the critical periods in the daily cycle when the tank is close to either overflowing or emptying.
- For the case of invariant cyclic input patterns investigated in Chapter 4, limits of 100 and 0 percent were used in the algorithm for the upper and lower hold-up limits, respectively. These were selected because it allows a direct comparison between results for different sized tanks (quoted on the basis of the

total tank volume). Once hold-up limits are specified between the extremes of zero and 100 percent direct comparisons with the results obtained when the extreme values are utilized are valid only to a degree.* In the proposed simulations of the real-time behaviour, the practical requirements make it impossible to use the extreme physical limits for the operational values; however, the values have been selected close to the extreme limits so that: (1) the results for different sized tanks can still be compared with those for the same tank sizes presented in Chapter 4; and (2) by selecting the limits close to the extreme values, a severe test is imposed on the capacity of the strategy to deal with the abnormal input conditions mentioned earlier.

- (2) Weighting factors (α , β , ω): The effects on equalization performance of the magnitudes of α , β and ω have been discussed extensively in Section 6, Chapter 3. Of these factors, only ω (the weighting factor for rate of change of outflow rate penalty error) was shown to exert an *indirect* influence on equalization performance under invariant input conditions by masking the effect of α . It is necessary therefore to investigate, in greater depth, the effect of changing the magnitude of ω to assess whether the same considerations apply in the selection of ω as before. This is done in Section 2.2. For our present purposes, except where stated otherwise, a value of $\omega = 20,0$ is selected on the basis of the results obtained under invariant inputs.

In the simulations equal weight will be ascribed to the importance of flow and load equalization by choosing $\alpha = 0,5$; this, very likely, will be a common selection in practice. Considering the penalty error weighting factor, β , this is

* Tank retention times are quoted in terms of the total tank volume and the mean daily inflow rate ($R_T = V_T/\bar{Q}$). Therefore, the limits of 5 and 95 percent effectively reduce the useful tank volume with respect to flow equalization by a factor of 0,90 and with respect to load equalization by a factor of 0,95. Comparison with invariant flow conditions and hold-up limits of zero and 100 percent in consequence, are not on an equal basis.

selected solely on the basis of ensuring that the objective of the penalty error for volume limits is served; therefore, the same value of $\beta = 2 \cdot 10^{-6}$ utilized in Chapter 3 is used in the simulations.

- (3) Length of control intervals: In the applications of the equalization algorithm under invariant input patterns (Chapters 3 and 4) it was found that the *adjustment interval length* of 0,5 hour led to satisfactory results for equalization tank sizes to be expected in practice i.e. for mean retention times exceeding 3 hours. For the purposes of this Chapter, a *control interval length* of 0,5 hour also will be used for the simulations of the control strategy as it is convenient for the practical implementation to have the two equal (see Chapter 7). Consequently, the optimal tank outflow rate will be specified every 30 minutes by applying the equalization algorithm under (1) the expected inputs for the ensuing 24 hours and (2) the actual tank hold-up at the corresponding time. However, it is advisable to analyze more extensively the factors that enter into the choice of the control interval length; these factors are similar to those involved in the selection of the adjustment interval length, and are discussed in Section 4.

Table 6.1 Some Process Parameters used in Simulations

Parameter	Value
Upper hold-up limit, V_{lu}	95 %
Lower hold-up limit, V_{lb}	5 %
α	0,5
β	$2 \cdot 10^{-6}$
ω	20,0
Length of Control Interval	0,5 h

Before discussing the various applications of the control strategy, some comment should be made regarding the starting conditions for the simulations. In the various examples below the procedure followed is identical to that used in the examples presented in Chapter 5 i.e. the simulations commence at 12 o'clock midnight, and cover a 48 hour period. To initiate the simulation it is necessary to specify a starting value of the tank hold-up and concentration; these values are taken in accordance with the expected values for that time of day indicated from the applications of the equalization algorithm in Chapters 3 and 4. This would appear to be a reasonable assumption considering that the tank parameters should be very close to those predicted by the algorithm had the control strategy been in operation prior to the start of the simulation - an assumption which is supported by the observation that, at the end of the simulations, (i.e. after two cycles), the tank hold-up and concentration are very close to the starting values.

2.1 Equalization Tank Size

Under invariant daily inputs, a general conclusion arising from the analysis of the effect of tank size on equalization efficiency (see Section 2.1, Chapter 4) was that, to provide efficient equalization, a 4 to 6 hour retention time tank is adequate. (The retention time is based on the mean daily inflow rate). It was shown that as tank retention time decreases below 4 hours the effluent flow rate and load patterns increasingly assume the character of the corresponding influent patterns; and, as the tank retention time increases above 6 hours the improvement in equalization efficiency is so marginal that it is unlikely that the slight improvement will merit the increased capital cost.

To check if the findings above are applicable also when operating the equalization tank under the control strategy, (i.e. under real-time inputs), three simulations of the controlled response of an equalization tank were performed. Tank retention times of 3, 5, 5 and 8 hours were selected, under inputs of flow rate and concentration measured at the Cape Flats WWTP over a Tuesday/Wednesday period. The results of the simulations are shown in Figs 6.1,

6.2 and 6.3.* These results should be compared with those obtained utilizing the equalization algorithm under invariant inputs to determine the optimal tank effluent profiles for the same respective retention times (see corresponding Figs 4.1, 3.5 and 4.4). The respective responses are very similar indicating that the control strategy appears to induce outflow rate and load profiles (on a continuous basis) that are near the "best" patterns obtained under invariant daily inputs.[†] This poses the question: Does this imply that the conclusions on the effect of equalization tank size, obtained from the analysis under invariant daily inputs, are also applicable under real-time inputs? To check this the same procedures employed to analyze the response under invariant input patterns in Chapter 4 will be repeated here. That analysis involved two approaches; namely, (1) a qualitative assessment involving a visual comparison of results obtained for different tank sizes; and (2) a quantitative assessment in which the relationship between a defined relative error, E_r , and equalization tank size was evaluated.

The *qualitative* visual assessment of the results for the three cases indicates the following points of interest:

- (1) For the 3 hour retention time tank the effluent flow and load rate patterns exhibit the same characteristics as the influent patterns i.e. the degree of equalization is ineffective, although some smoothing of the patterns occurs as a result of the buffering action of the tank.
- (2) The full tank capacity is utilized in the 3 hour tank whereas the minimum hold-up with the 8 hour tank is 36 percent of the total - it is because of this large "reserve" capacity that very good *load* equalization is obtainable with the 8 hour tank.

* Figure 6.2 for the case of a 5.5 hour tank has already been shown in Fig 5.2, Chapter 5; this Figure is again shown here for convenience.

[†]In this example the Tuesday/Wednesday inputs are very similar to both one another and the historical influent patterns; it may be argued that the results obviously should be very close to the optimal results. However it should be noted that the simulation results under the control strategy are obtained without the restriction of a mass balance, whereas in Chapter 3 a mass balance was basic to the optimal solution.

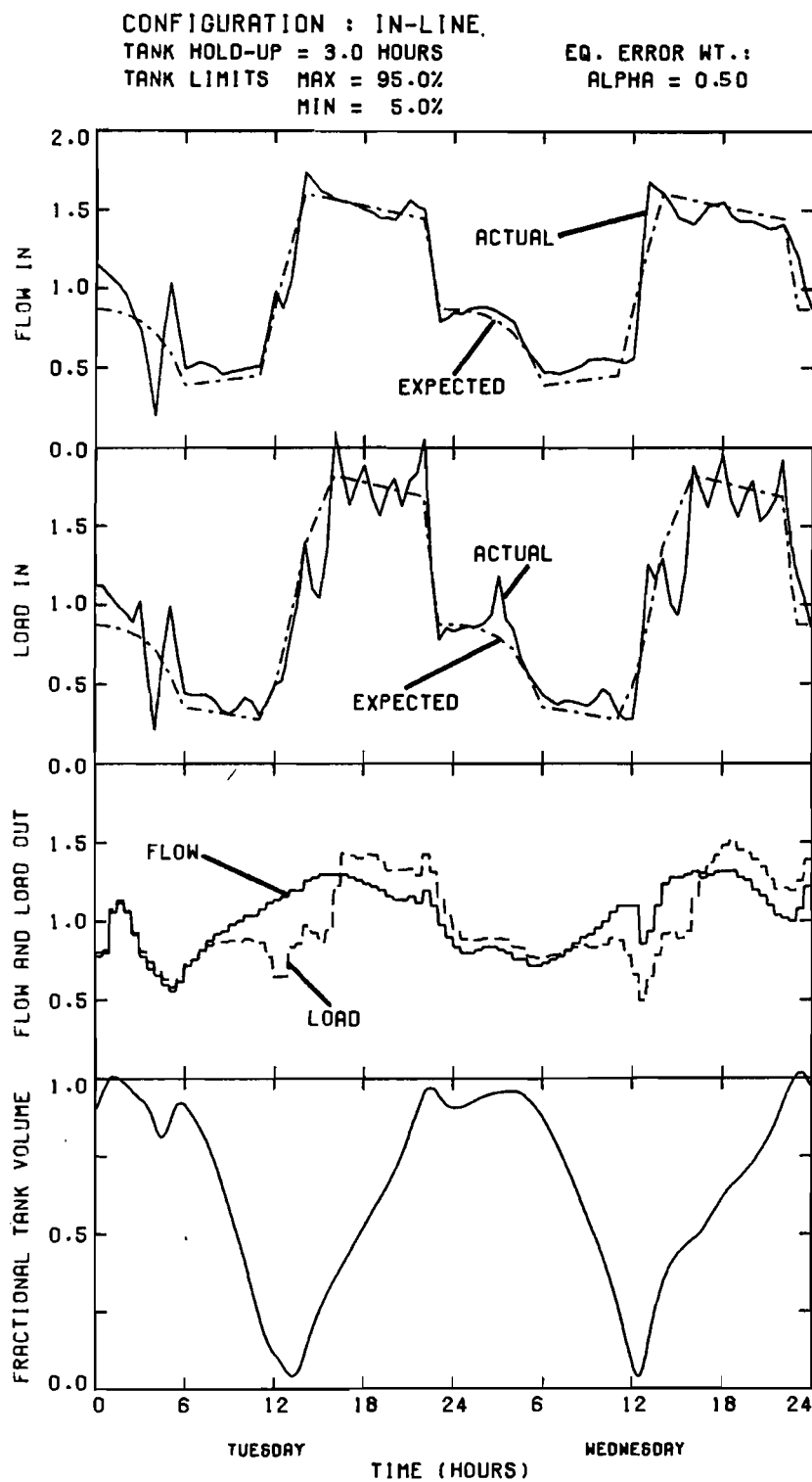


Fig 6.1 Simulation of controlled response of an in-line equalization tank with a mean retention time of 3 hours (Cape Flats data).

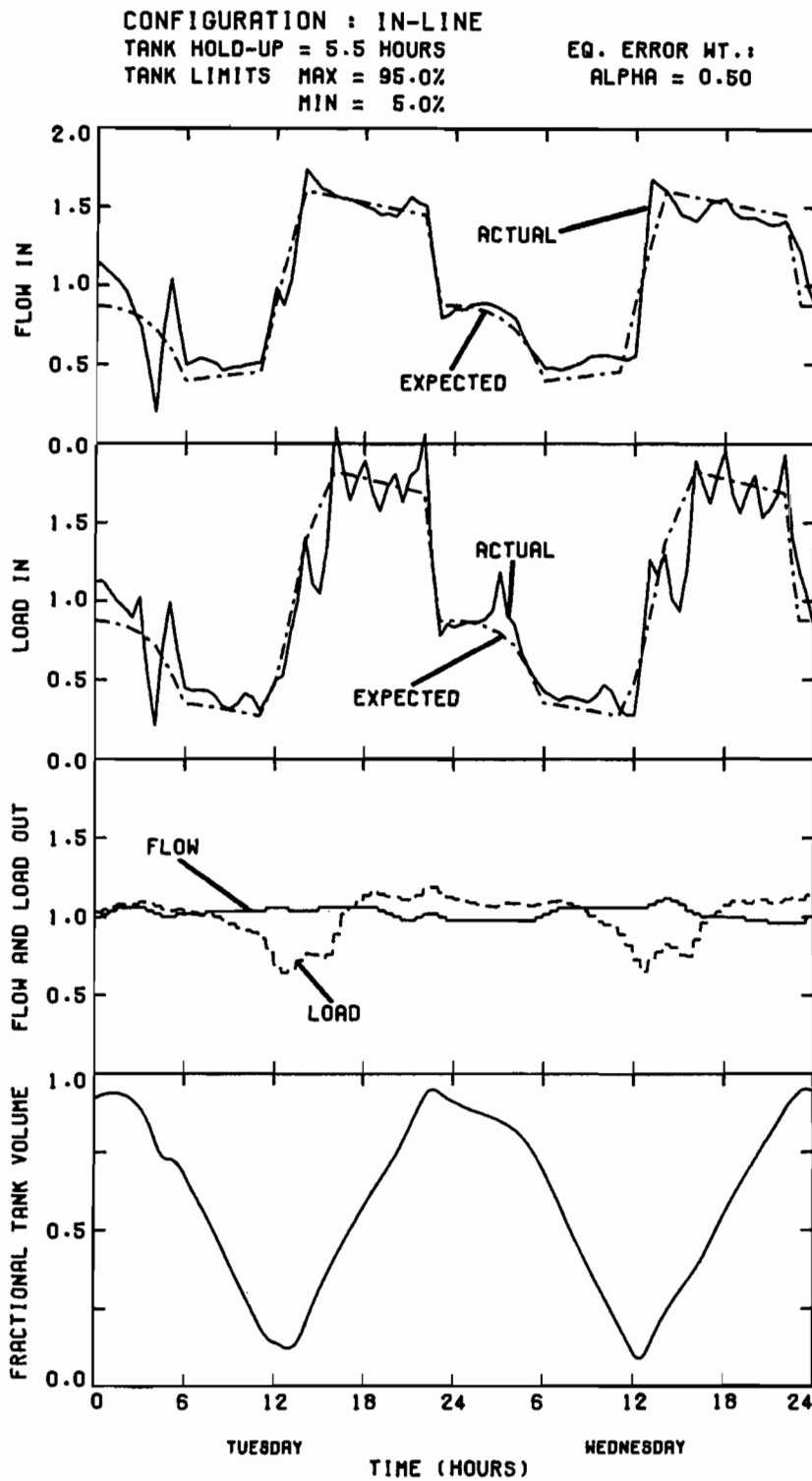


Fig 6.2 Simulation of controlled response of an in-line equalization tank with a mean retention time of 5.5 hours (Cape Flats data).

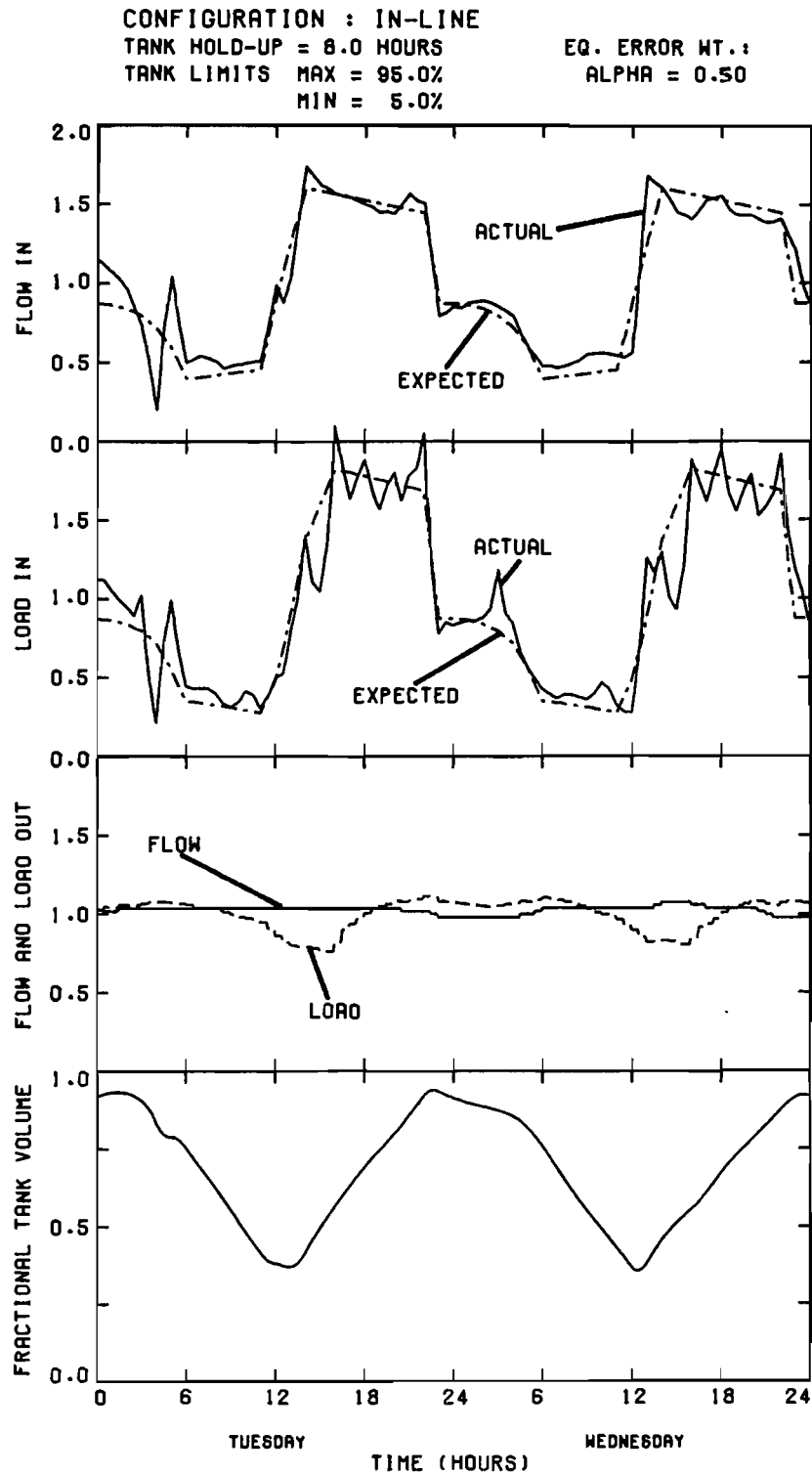


Fig 6.3 Simulation of controlled response of an in-line equalization tank with a mean retention time of 8 hours (Cape Flats data).

- (3) There is relatively little difference between the response of the 5,5 hour and 8 hour tank. Both tanks lead to similar degrees of equalization so that subjectively there is little merit in selecting an 8 hour retention time tank - the increased capital cost will not merit the marginal improvement in equalization efficiency.

The above observations are clearly in conformity with those listed in the qualitative analysis of the effect of equalization tank size under invariant daily cyclic input patterns (Section 2.1, Chapter 4).

The *quantitative* assessment of the results is provided by plotting the relative error, E_r (defined by Eq 4.1) versus equalization tank retention time as utilized in Chapter 4. Under *invariant* inputs the curves of relative error, E_r , versus tank retention time are continuous, reflecting a one-to-one relationship i.e. a single value of E_r is associated with each value of retention time. Under real-time inputs for a two-day period with half-hour control interval lengths, the relative error can be computed 96 times for the following reason:

Under invariant flow and load input conditions the equalization algorithm is applied only once in order to calculate the optimal outflow rate profile i.e. only one E_r value is associated with each application of the algorithm. With the control strategy the algorithm is applied every half-hour in order to optimize the output continuously to account for the differences between the actual and the historical input patterns; this means that simulation for a two-day period gives rise to 96 error values. If the actual input patterns conform identically to the historical patterns then all 96 E_r values will be equal. However, because there are differences between the actual and historical input patterns there will be a number of different E_r values for each simulation.

The ranges of E_r values obtained in the simulations for each of the three tank sizes are plotted in Fig 6.4 together with the E_r curve

for the case of invariant input patterns (from Fig 4.5). Several features regarding the results shown in Fig 6.4 can be noted:

- For each tank size the values of E_r obtained from each application of the equalization algorithm range about the value of E_r obtained under invariant input patterns.
- With increasing tank size, the range of E_r values decreases; this phenomenon is to be expected because the effect of differences between the actual and expected input patterns will be less marked for larger equalization tanks.
- The overall impression from Fig 6.4 is that the results confirm the observation regarding the effect of tank size on equalization efficiency obtained from the analysis under invariant daily input patterns i.e. the E_r value decreases rapidly with increasing tank size up to a retention time of approximately 4 hours and then decreases less rapidly with further increases in tank size.

There is little reason in attempting a more detailed analysis of the effect of equalization tank size on the control strategy performance - it is clear from the presentation above that the conclusion regarding the effect of retention time on equalization efficiency for invariant input patterns is essentially also valid under real-time input conditions i.e. for inputs of flow and load typically encountered at a WWTP, effective equalization requires a 4 to 6 hour retention time tank. This is still subject to the proviso, of course, that differences between actual inputs from day to day are not too great.

2.2 Penalty Error for Rate of Change of Outflow Rate - Weighting factor ω .

In the development of the equalization algorithm a constraint was imposed on the rate of change of the outflow rate from the equalization tank. This was achieved by including a component in the error expression, weighted by a factor ω , to penalize the development of an outflow profile that exhibits any rapid changes. The purpose of this penalty error was actually two-fold: (1) to ensure the development of a "smooth" outflow profile which is free from spikes

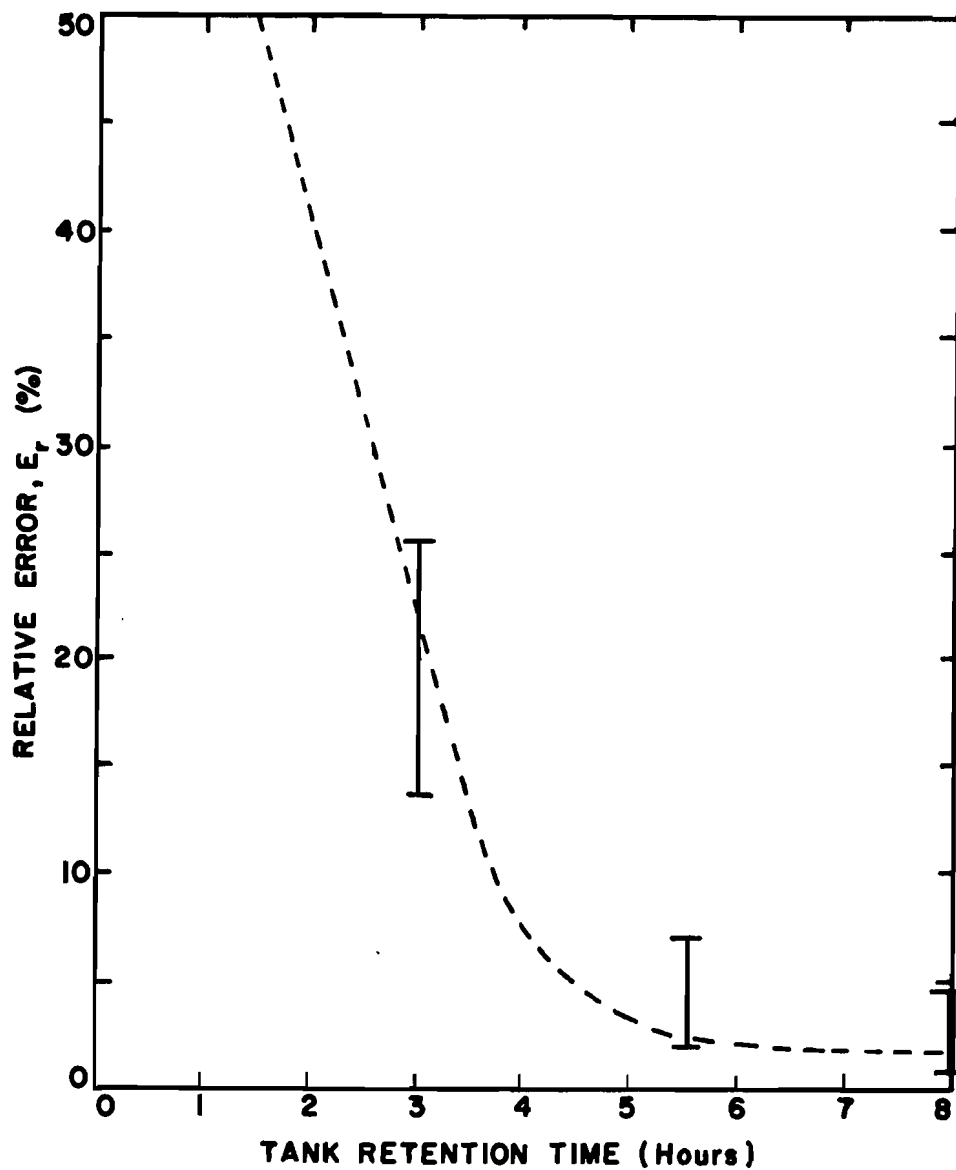


Fig 6.4 Ranges of relative error, E_r , for three equalization tank sizes. (Dotted line shows E_r vs R_T curve for invariant daily inputs).

induced by the mathematical optimization procedure, and (2) because rapid changes in flow rate will affect the downstream process adversely. It was shown in Section 6.3, Chapter 3, that the effect of increasing the weighting factor w is to increase the importance of flow equalization relative to load equalization. For this reason it was stated that the magnitude of w should be

such that it serves the objectives of the penalty error, and yet does not mask the function of the equalization error weighting factor, α .

With regard to the rate of change of outflow rate penalty error in the application of the equalization algorithm in the control strategy it is necessary, firstly, to investigate whether the function of this error component is still required, and secondly, if this is so, to enquire into the effect of ω on the equalization results; this will bring to the fore the considerations that enter into the selection of the magnitude of ω .

Necessity for Rate of Change Penalty Error: From simulations under real-time inputs it was found that the penalty error does, in fact, serve a useful purpose. Consider the situation where, say, the inflow is stopped for some reason. The desired action would be to induce a gradual decrease in the outflow rate in steps until the inflow is resumed rather than inducing a very sudden large change (unless this was absolutely required because of the volume limits - an aspect in any case governed by the volumetric limit penalty error). The gradual reduction would be the indicated result from including the penalty error for rate of change of outflow rate.

Selection of ω : The magnitude of ω can be selected only on the basis of a subjective evaluation of the results obtained using different ω values. To illustrate this, two sets of responses are presented in which ω is assigned values of 5,0 and 50,0, respectively, while all other parameters are held constant; these are shown in Figs 6.5 and 6.6 respectively, for the controlled response of a 5,5 hour in-line tank over the Tuesday/Wednesday period. Comparison of the two Figures clearly shows that, when ω is large, the algorithm tends to reduce the number of changes in outflow rate; in addition, the concomitant effect is to favour flow equalization relative to load equalization despite equal weight being assigned to each in terms of the equalization error weighting factor, α ($\alpha = 0,5$ for both cases).

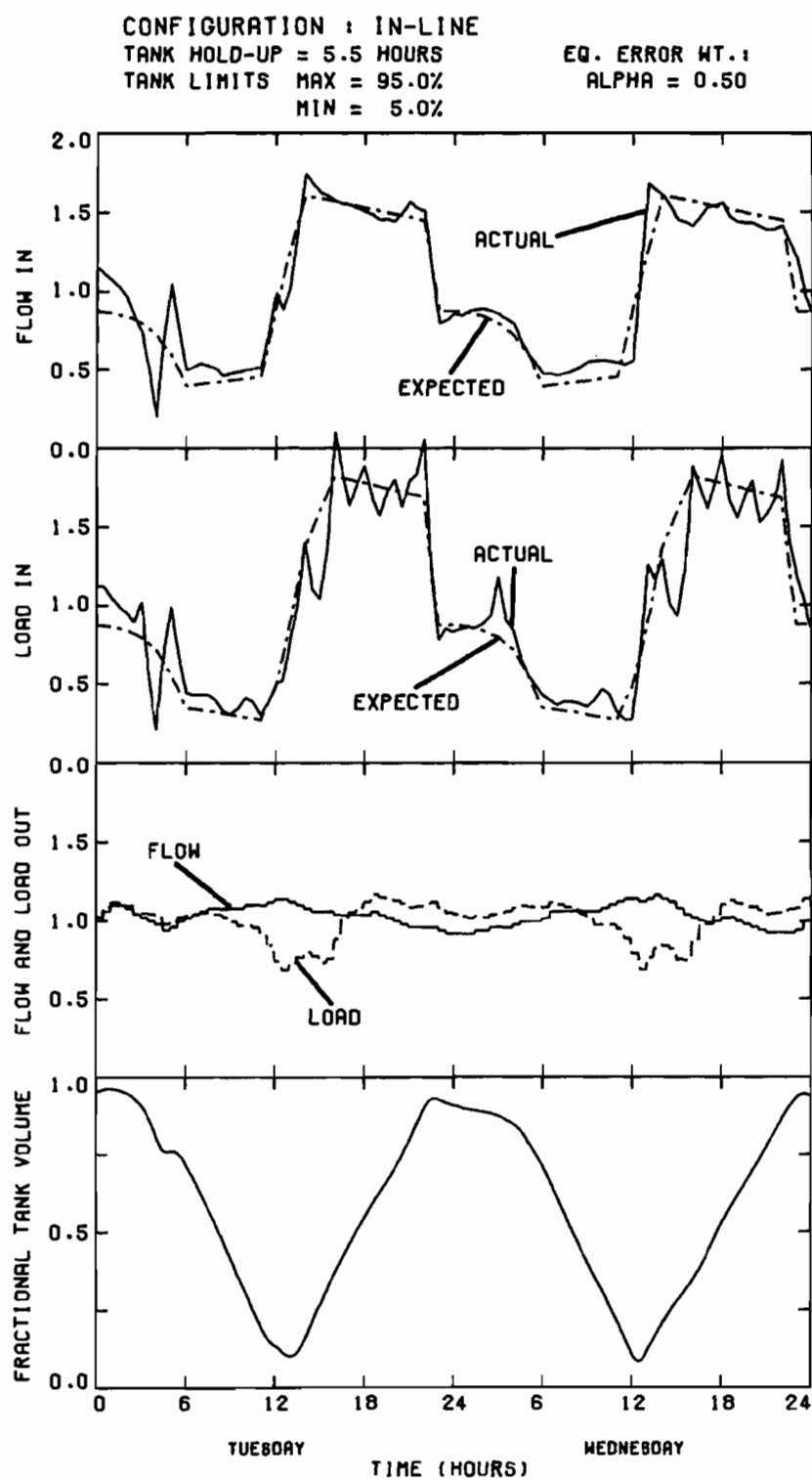


Fig 6.5 Simulation of controlled response of an in-line equalization tank where $\omega = 5,0$.

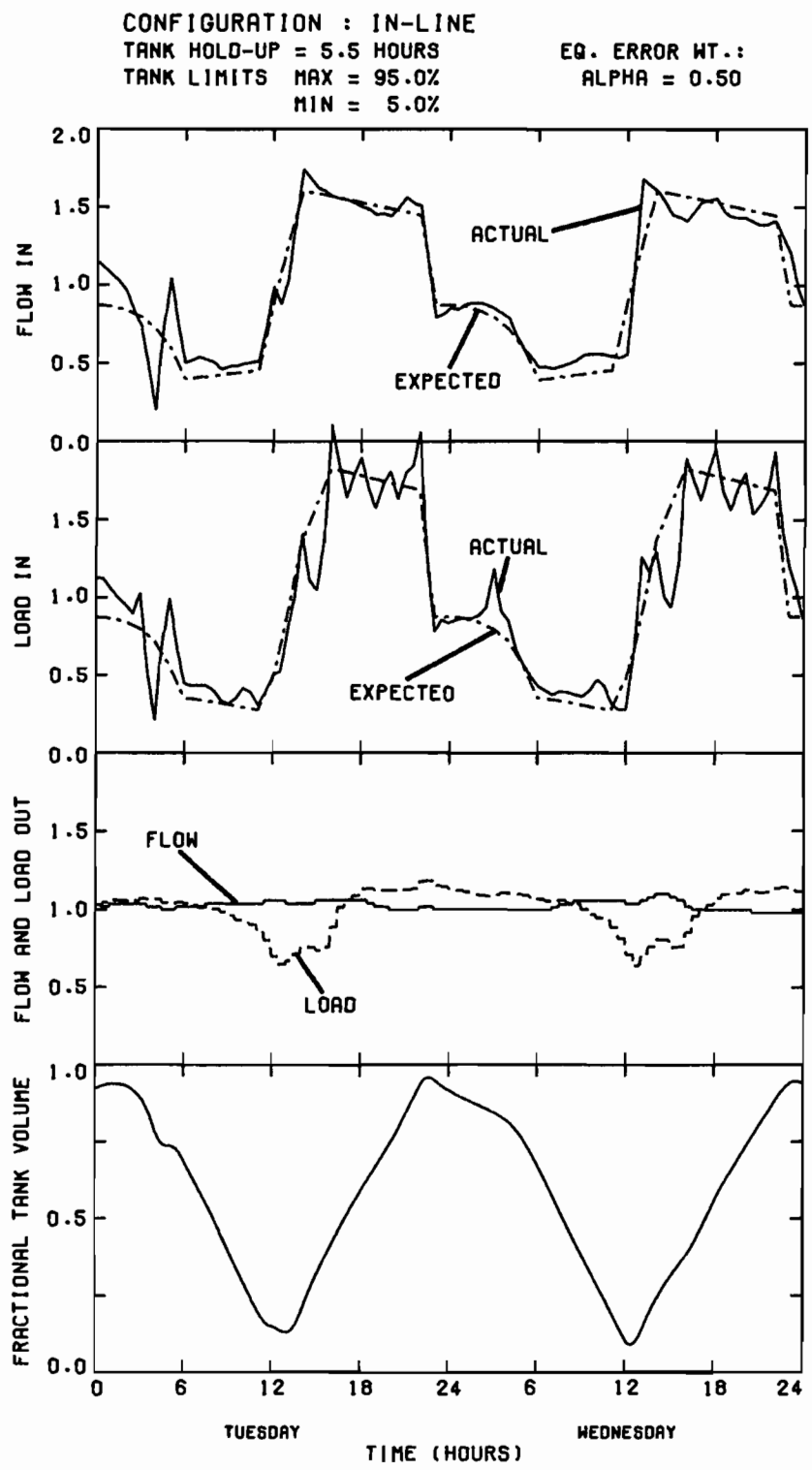


Fig 6.6 Simulation of controlled response of an in-line equalization tank where $\omega = 50,0$.
(cf. Fig 6.5 where $\omega = 5,0$).

To retain the function of the penalty error without exercising too great an influence on the equalization effect it would seem that ω should be selected in the range of 5,0 to 50,0. In the remaining simulations a value of $\omega = 20,0$ is used; however, this choice is still a subjective one - ω should be selected specifically for each individual application of the control strategy.

2.3 Equalization Facility Configuration

Simulations of the controlled response of an equalization facility presented so far in this Chapter and in Chapter 5 have been restricted to the case of in-line configurations, where all the influent flow passes via the equalization tank to the downstream process. The results have shown that, for in-line equalization, conclusions drawn from the analysis of equalization behaviour under invariant daily input patterns of flow and load (Chapter 4) also hold when the equalization algorithm is used in a control strategy under real-time inputs of flow and load. It now remains to see whether conclusions regarding the performance of side-line equalization facilities can also be extended to the case of real-time inputs of flow and load.

The most important conclusion drawn from the analysis of side-line equalization under invariant daily input patterns in Section 3, Chapter 4, is that, irrespective of the method of flow division (splitting or topping), side-line equalization does not lead to any reduction in volume requirement for an effective degree of equalization when compared to the in-line case. That is, whether an in-line or a side-line configuration is employed, effective equalization requires a tank volume with a retention time (based on the *total* inflow to the plant) in the region of 4 to 6 hours - under invariant daily input patterns this is true irrespective of the fraction of the daily influent flow diverted via a side-line equalization tank, provided this is at least 40 percent of the total inflow, i.e. less than 60 percent of the inflow passes directly to the downstream process. Therefore, the only motivation for selection of a side-line configuration over an in-line configuration is the possible

saving in pumping costs in cases where plant topography does not allow for gravity flow through the equalization facility.

In side-line equalization an important adverse feature, compared to in-line equalization, is apparent when the practical operation of a side-line facility is considered. In practice rapid random fluctuations about the average (trend) patterns are encountered for both the influent flow rate and concentration; where there is a division of the influent stream, with one stream bypassing the equalization tank, the influent fluctuations will be partially transmitted to the downstream process. In contrast, with in-line equalization, where none of the influent flow bypasses the equalization tank, the tank acts as a buffer for the influent fluctuations, and no portion of either the flow or concentration fluctuations can be passed directly to the downstream process. It would appear, therefore, that this aspect, depending on its severity, will be of key importance in the selection of the equalization configuration.

The degree to which influent flow and/or concentration fluctuations are transmitted to the downstream process is related, *inter alia*, to the method of flow division (Chapter 4). For this reason, application of the control strategy for the cases of flow splitting or flow topping needs to be considered separately.

2.3.1 Side-line Equalization with Flow Splitting

With flow splitting there is a continual division of the influent flow in some fixed proportion, i.e. at any instant a fixed proportion of the inflow bypasses the equalization tank. Any rapid random variations in *both* the influent flow rate and concentration, therefore, are similarly divided on a continuous basis. To assess the extent to which this behaviour is likely to affect the efficiency of equalization, a simulation of the controlled response of a 5,5 hour retention time side-line equalization tank under inputs of flow rate and concentration measured over a Tuesday/Wednesday period at the Cape Flats WWTP, is presented in Fig 6.7. In this example a value of the flow division factor, $\gamma = 0,50$ is used, i.e. 50 percent of

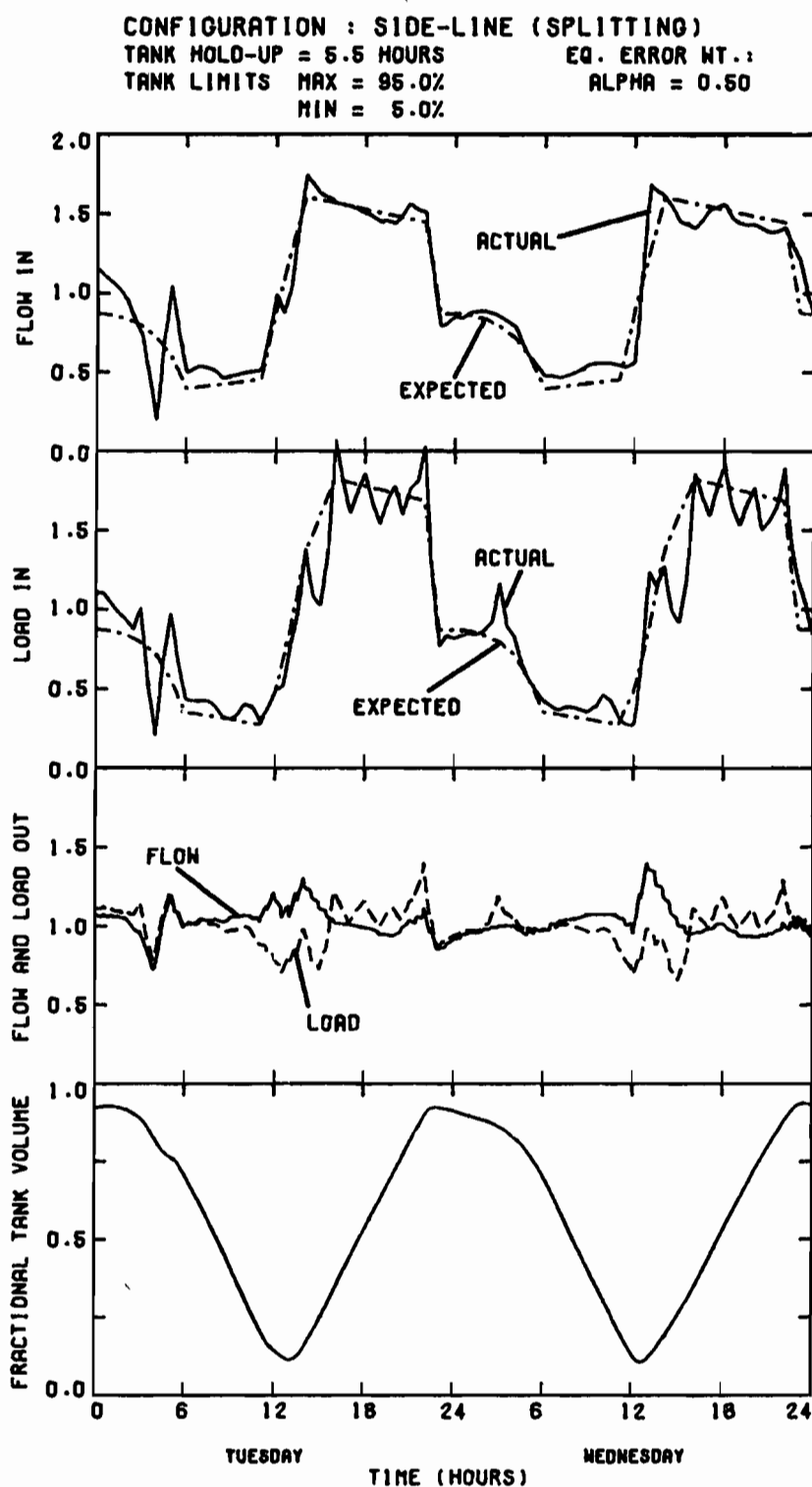


Fig 6.7 Simulation of the controlled response of a 5,5 hour mean retention time *side-line* equalization tank with flow division by *flow splitting* ($\gamma = 0,50$).

the inflow continuously bypasses the equalization tank. The results in Fig 4.14, Chapter 4, which show the relative error, E_r , plotted versus flow division factor, γ , indicate that this choice of parameters (tank size, γ) should lead to essentially the same degree of equalization as would be obtained with an in-line tank of the same size. Therefore, the results presented in Fig 6.2 for the case of an *in-line* equalization tank of the same size and under the same inputs of flow and concentration, form a basis for assessing the results of Fig 6.7. Comparison of Figs 6.2 and 6.7 identifies the following features:

- The efficiency of equalization of both flow and load is far greater with in-line than with side-line equalization.
- With respect to the *flow rate*, the peak flow rate of the stream entering the downstream process is 1,4 times the mean (cf. 1,1 times the mean for in-line) and the minimum flow rate is 0,7 times the mean (cf. 0,95 times the mean for in-line).
- With respect to the *load rate*, the corresponding peak and minimum are respectively 1,4 and 0,65 times the mean load rate (cf. 1,2 and 0,65 respectively for in-line).
- Whereas, with in-line equalization both the equalized flow and load rate patterns are relatively "smooth", with side-line equalization the patterns both exhibit rapid random fluctuations in accordance with the fluctuations in the influent stream; the magnitude of these fluctuations will be approximately half that of the influent (for the case considered here) as half of the influent stream bypasses the equalization tank.

The comparison above between in-line equalization and side-line equalization with flow splitting clearly shows that, in terms of equalization efficiency, the in-line configuration is the preferable one. The in-line configuration not only leads to superior equalization of both flow and load, but also results in relatively

smooth flow and load rate patterns. The latter aspect will result in simplified in-plant control over that required for the side-line case.

In side-line equalization with flow splitting the only means for reducing the extent to which influent fluctuations are passed to the downstream process is to reduce the fraction of the influent flow which bypasses the equalization tank, i.e. to move in the direction of an in-line configuration. This action, however, will be contrary to the objective in using a side-line configuration which is to increase the amount of flow bypassing the equalization tank in order to reduce pumping costs where gravity flow through the tank is not possible. It therefore would appear unlikely that side-line equalization with flow splitting will provide satisfactory equalization performance under real-time conditions if the maximum benefit of a reduced pumping cost is to be realized. The pertinence of this conclusion is particularly borne out by the example presented here (Fig 6.7); the fluctuations about the historical influent patterns are not particularly severe, yet their effects are very evident in the output profiles.

2.3.2 Side-line Equalization with Flow Topping

Where the method of flow division in side-line equalization is flow topping, only influent flows over a certain rate are diverted to the equalization tank. Therefore, over parts of the day when the influent flow rate drops below the specified cut-off value all the influent flow bypasses the equalization tank; over the remaining parts of the day the flow rate of the stream bypassing the tank is constant. In terms of the influent fluctuations which are transmitted directly to the downstream process, there are two situations:

- When the influent flow rate exceeds the cut-off value no influent flow rate fluctuations are transmitted; however, concentration fluctuations are transmitted.
- When the influent flow rate is less than the cut-off value no flow is diverted to the tank and both flow-rate and concentration fluctuations are transmitted to the downstream process.

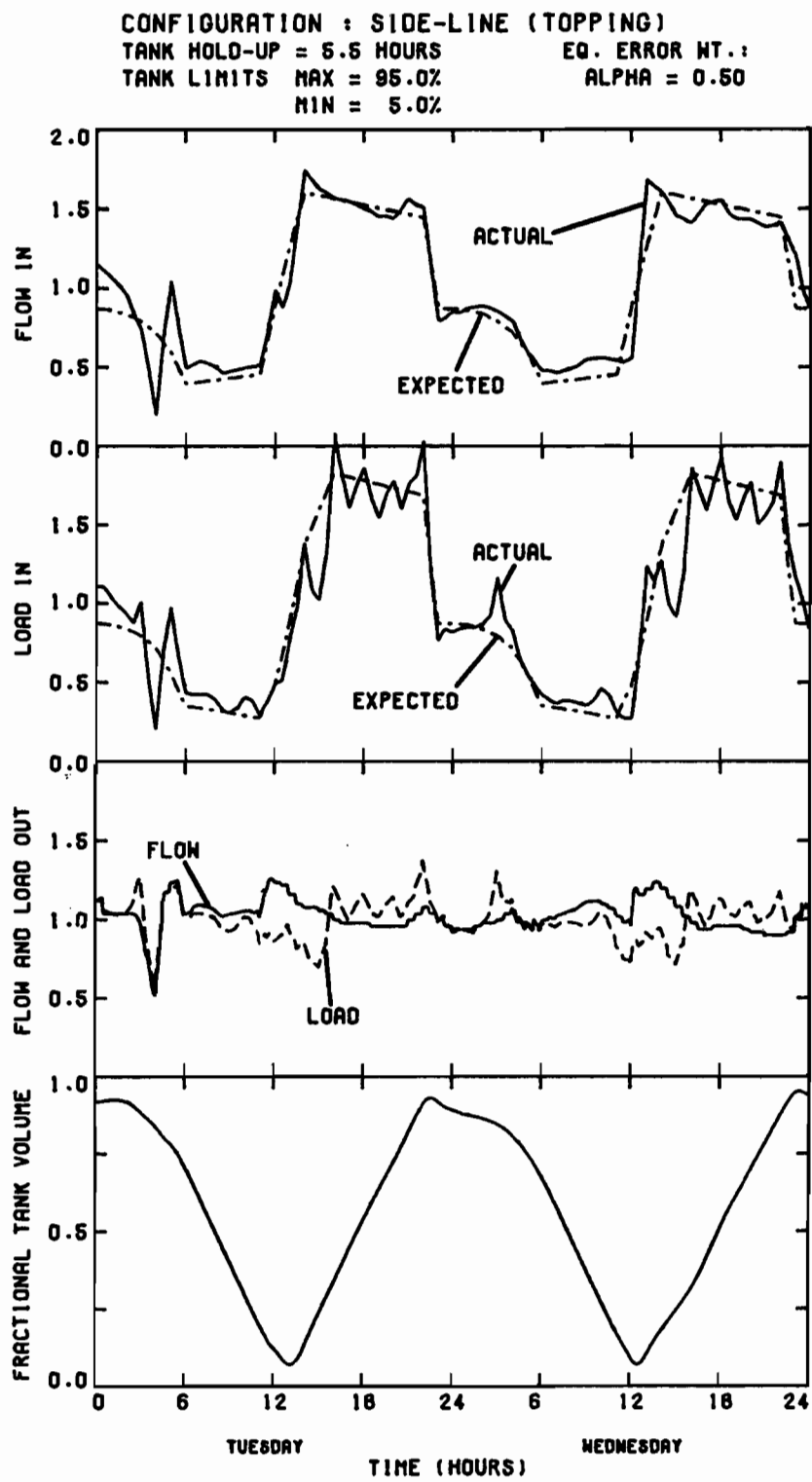


Fig 6.8 Simulation of the controlled response of a 5,5 hour mean retention time *side-line* equalization tank with flow division by *flow topping* ($\gamma = 0,70$).

To assess the extent to which this method of flow division is likely to affect equalization efficiency we consider the same case as that used for flow splitting in the previous Section; simulation of the controlled response of a 5,5 hour retention time side-line equalization tank, under the same inputs of flow rate and concentration measured over a Tuesday/Wednesday period at the Cape Flats WWTP, is presented in Fig 6.8. A value of the flow division factor, $\gamma = 0,7$ is used in the example,^{*} i.e. flows in excess of 0,7 times the historical average inflow rate are diverted to the equalization tank.

Comparing the effluent responses in Fig 6.8 (side-line with flow topping) and Fig 6.7 (side-line with flow splitting) with Fig 6.2 (in-line), it is apparent that:

- Generally the effluent response from the equalization tanks in the side-line configuration (with either flow splitting or topping) is not as efficient as the in-line equalization tank with respect to both flow and load equalization.
- With flow topping there is, perhaps, a marginal improvement in the quality of the *flow* equalization compared with that obtained with flow splitting. This is to be expected because, whereas with flow splitting influent flow rate fluctuations always are present in the stream bypassing the tank, with flow topping the flow rate of that stream is constant at least over a portion of the daily cycle.
- The effluent load rate patterns are almost identical with either flow splitting or flow topping; therefore, problems with regard to downstream aeration control might be encountered, due to the "spikiness" of the load pattern.

In flow topping, as with flow splitting, the only method for reducing the direct transmittance of influent fluctuations is to reduce the fraction of flow bypassing the balancing tank. Such action again is in conflict with the objective of reducing pumping costs to or from the equalization tank.

* In the literature a value of $\gamma = 1,0$ is often encountered i.e. only flows in excess of the mean flow rate are diverted to the equalization tank. However, from the analysis of flow topping under invariant daily input patterns (Section 3.2, Chapter 4), the optimal value of γ for the Cape Flats input patterns lies in the range 0,6 to 0,8.

2.3.3 Selection of Configuration : In-Line versus Side-Line

On the basis of the results presented in Sections 2.3.1 and 2.3.2 it would appear that a general conclusion regarding the selection of process configuration for real-time operation is:

When gravity flow through an equalization facility is possible (and a possible saving in pumping costs is not a factor), an in-line configuration clearly is to be preferred over a side-line configuration with flow division either through splitting or topping.

This conclusion is formulated solely on the basis of the efficiency of equalization and considerations arising from this with regard to downstream process control. In addition to this aspect, other factors also favour the selection of an in-line configuration. For example:

Construction requirements: An in-line configuration is likely to be more simple, and probably less costly, than a side-line configuration. The side-line configuration will require a tank bypass channel, a specially constructed flow division arrangement, and an additional sump to re-mix the two streams before entering the downstream process.

Implementation requirements: Implementation of the equalization control strategy for an in-line equalization tank requires measurement of (1) tank outflow rate and (2) tank hold-up; influent flow rates required for updating historical data and determining expected inflow profiles are obtained by calculation from hold-up changes over an interval, knowing the tank outflow rate. In side-line equalization computation of influent flow rate from hold-up changes is only possible when flow splitting is used; with the continuous division of inflow in a *fixed* proportion, the inflow rate to the tank is directly related to the total inflow rate. However, with flow topping this is no longer possible as the flow to the tank is not directly related to the total inflow. Therefore, implementation of the control strategy in a side-line scheme

with flow topping requires measurement of the influent flow rate in addition to the measurement of tank outflow rate and hold-up.

In light of all the factors favouring the selection of an in-line configuration, and the fact that no saving in volume requirement is achieved with side-line equalization, very strong motivation would be required before a side-line configuration could be preferred to an in-line configuration. Such motivation, as is generally accepted, is the saving in pumping costs where gravity flow through the equalization facility is not possible. However, to realize an appreciable saving would require very unusual circumstances (such as particularly exorbitant electricity costs) because the results show that only a small fraction $\frac{1}{10}$ of the influent flow may bypass the equalization tank without exerting too detrimental an effect on the quality of equalization.

3. CONTROL STRATEGY PERFORMANCE UNDER UNUSUAL INPUTS

A general feature apparent in the examples of controlled response of an equalization tank presented in Chapter 5 and this Chapter is that differences between the actual and the historical influent flow rate and concentration patterns have been relatively small. However, a number of situations can be identified which cause large deviations from the expected patterns:

- (1) It is quite common to observe large fluctuations away from the historical patterns, but usually the fluctuations are of short duration and, more often than not, a fluctuation in one direction away from the expected input is partially offset by similar fluctuation occurring directly after the previous one, but in an opposite direction. Influent flow rate and concentrations that oscillate at relatively high frequency about the historical input patterns tend to cause little trouble in control strategy operation as the combined effect is self-compensating. Difficulties only arise where the deviation of the actual from the historical input is sustained in one direction for an appreciable period. Two

such situations are detailed in (2) and (3) below:

- (2) At certain extreme states with regard to the tank hold-up, for example, when the tank hold-up is close to its lower limit, a delay in the historically-expected rapid increase in the influent flow rate after the period of minimum inflow may cause the tank to empty below the absolute minimum allowable level (e.g. floating aerators may require a minimum depth). If the delay persists then some form of *emergency control* will be required to ensure that the minimum hold-up is maintained.
- (3) A *rain-storm* in the wastewater collection area causes an appreciable ingress of storm water into the sewer system, resulting in a hydraulic shock load on the equalization facility.* A particularly critical condition will be created if this occurs when the tank is close to its upper hold-up limit. Consequently, some emergency action may be required in the strategy for this type of occurrence.

Before discussing the effect of (2) and (3) above on the response behaviour and the consequential counter-action to be built into the control strategy it is worth commenting on the fact that neither event is specifically related to the influent concentration pattern; both involve hydraulic effects. Two features combine to give precedence to the importance of unusual flow effects over concentration effects:

- The earlier examples have shown how, under normal conditions, the control strategy successfully exploits the equalization capacity to achieve the objective of providing near-optimal operation on a continuous basis. However, under unusual input patterns, the equalizing capacity of the facility becomes "over-stressed" for the duration of the unusual event

* This investigation has been restricted to the study of systems where storm water drains and sewers are separate. However, even where separate systems are employed (as is generally the case in South Africa), a certain amount of ingress will occur with storms, depending on the state of repair of the sewer system and the amount of policing by municipal authorities to ensure that illegal addition of storm water to sewers is minimized.

(and perhaps for a time after the event); in this case the action of the control strategy should be to return to optimal operation in the best possible manner. In most cases "over-stressing" of an equalization facility will cause the physical volume limits of the tank to be exceeded; for this reason unusual events relating to influent *flow* behaviour achieve prominence.

- The control strategy proposed in this investigation does not include continuous monitoring of concentration; consequently, it is evidently impossible to cater for unusual concentration inputs.

3.1 Emergency Control Procedures

For any particular equalization facility certain physical limitations may exist which, under no circumstances, should be exceeded even though this may require overriding the action of the control strategy. An example of such a situation is where, as a result of certain inflow behaviour, the tank hold-up would drop to unacceptably low levels if the tank outflow rate is set by the equalization algorithm; in this case the outflow rate setting specified by the equalization algorithm should be disregarded, and emergency action taken to reduce the outflow rate so as to allow the hold-up to increase. Consider a case where, say, floating aerators are used for mixing the contents of the equalization basin; assume that an absolute minimum depth of 10 percent of the total tank hold-up is required to ensure that the aerators are never damaged. The approach used in utilizing the equalization algorithm would be as follows:

The algorithm requires maximum and minimum allowable tank hold-up limits to be specified; in this case the lower limit typically would be set at, say, 15 percent of the total tank hold-up. In the day-to-day operation, the tank hold-up would seldom fall below about 13 percent, depending on differences encountered between actual and expected inflow rates at times when the tank hold-up is close to the lower limit.* If,

*The expected inflow profile utilized by the equalization algorithm consists of the historical profile, together with an adjustment depending on differences between actual and historical inflow rates prior to the expected profile being determined (see Section 3.2, Chapter 5)

however, the actual inflow rate for some reason is substantially less than the historical inflow rate for an extended period at this time, then the *optimal* outflow rate may cause the tank hold-up to drop even below 10 percent of the total. As this is not acceptable, it would be necessary to reduce the outflow rate, ignoring the *optimal* value specified by the algorithm, until the tank hold-up attains an acceptable level.

The mechanisms which must be incorporated in the control strategy to ensure that fixed physical limits are never exceeded will differ, most probably, from one equalization facility to another; therefore it is not possible to prescribe a fixed set of emergency control procedures which will find general application. Consequently, the objective here is to draw attention to the possible need for such procedures; once the need for a particular procedure is identified, steps can be taken to include this procedure in the control strategy.

In this investigation only one "emergency" situation is considered; that of preventing tank hold-up dropping below a fixed level. The method used here for preventing this occurrence is as follows:

In the normal operation of the strategy the tank level needs to be monitored at the beginning and end of each control interval to supply information for calculating the mean inflow rates. In all the previous simulations, control interval lengths of 30 minutes have been used; during this interval the maximum change in hold-up generally does not exceed 3 to 4 percent of the total hold-up, and the requirements for control are satisfied. If, during the period when the tank is near the lower limit, the inflow rate remains below the expected value, but the outflow is set according to the expected inflow, the percentage change in hold-up during the half-hour may be sufficient to cause the tank level to fall below the absolute minimum. To prevent this occurrence it is necessary to monitor tank hold-up at shorter intervals within the control interval. This type of measurement can be obtained readily at short intervals, and also allows computation

of the mean inflow rate over the short interval (because the outflow rate is known). With these two pieces of information the following can be accomplished: A check can be maintained on the hold-up, and the emergency control mechanism is activated when the hold-up drops to, or below, some fixed lower limit (less than the lower limit used by the algorithm); at this point the outflow rate is set equal to the inflow rate calculated for the previous short interval to prevent the tank hold-up dropping further. Once the hold-up rises to an acceptable level the control strategy returns to optimal control.*

To demonstrate the emergency control procedure, the simulated controlled response of a 5,5 hour retention time tank under inputs of flow rate and concentration measured over a Monday/Tuesday period at the Cape Flats WWTP is presented in Fig 6.9. The important feature of the influent patterns is that, on the Monday, the rapid increase in the inflow rate after the period of minimum inflow lags behind the historically-expected increase by about 1,5 hours. To ensure that the emergency control procedure is activated the lower tank hold-up limit used by the equalization algorithm is specified as 5 percent of the total hold-up, while it is assumed that the fixed minimum hold-up is 3 percent (a difference of only 2 percent). In this example control interval lengths of 30 minutes are used, with emergency control interval lengths of 5 minutes i.e. the hold-up is checked 5 times between the beginning and end of each control interval.

Up to 10h30 the operation of the facility is close to the optimum; the tank outflow rate is being increased partially to sustain the load rate. At 11h30 the outflow rate is decreased slightly because the inflow rate has still not increased and the tank level is dropping. At 12h00 the tank hold-up reaches the limit of 3 percent; immediately the tank

*The mechanism used in this study may appear to be rather crude; however, it suffices to note that attention is only being drawn to possible emergency requirements - no fixed solutions are being proposed.

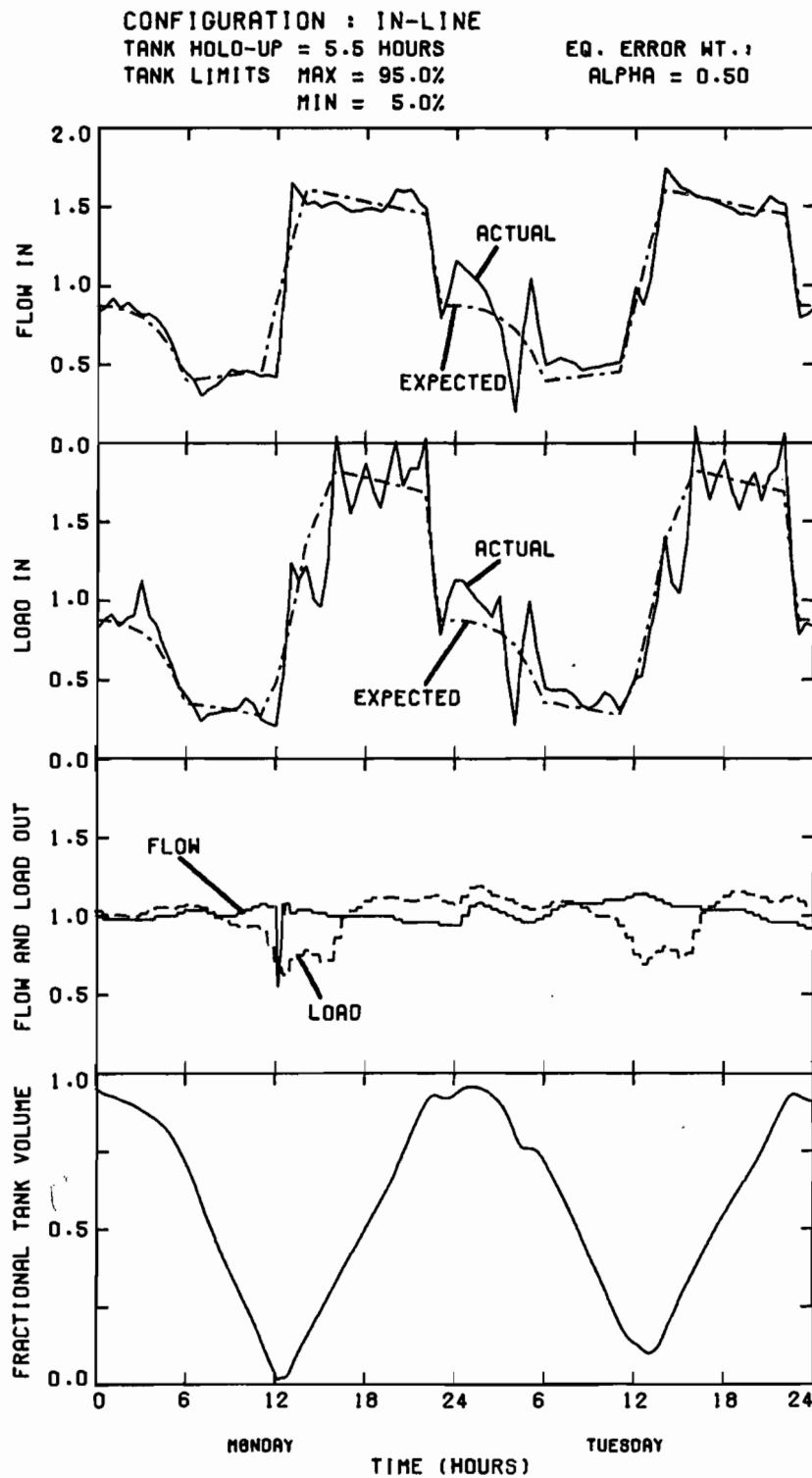


Fig 6.9 Example of emergency control action required to prevent tank hold-up dropping below a specified minimum limit.

outflow rate is reduced to equal the inflow rate. This continues for approximately half an hour until the hold-up increases to above 3 percent; thereafter the outflow rate returns to the optimal value specified by the equalization algorithm.

3.2 Control Strategy Performance under Storm Inputs

Storm water flows cause an hydraulic shock load resulting from ingress of storm water into the sewer system during and after a rain storm. It has already been noted that, where the storm drains and sewers are separate, the effect of storms on the influent patterns to a WWTP should be minimal; however, if it is accepted that the effect, in fact, is appreciable then the first step in assessing the influence of a storm input is to quantify the input. To this end three questions must be answered:

- (1) What will be the *form* of the influent flow rate and concentration patterns? In the case of the influent flow rate pattern, the first assumption made here is that the normal activities in the collection area are not affected, and any additional flow due to the storm is merely superimposed on the actual wastewater influent pattern*. Once this is accepted the question becomes one of selecting the form of the storm water flow pattern which arrives at the plant. This selection is a subjective one as many influences will determine the actual form. However, in keeping with the hydrologist's approach, it was decided to accept the following pattern:

From the moment the storm flow reaches the plant, the storm flow rate increases (from zero) at a constant rapid rate to a maximum, and thereafter decreases, also at a constant, but slower rate, until the storm flow becomes zero. The rates of increase and decrease are discussed later.

*The implicit assumption here is that the sewers are able to carry the extra flow without influencing the wastewater flow rate.

The nett effect is that the form of the storm flow is a skew triangle, as shown in Fig 6.10, which is then superimposed on the usual inflow pattern to give the actual inflow rate pattern for use in the simulations. The validity of this approach would appear to be reasonable when the inflow data collected at one full-scale plant over a storm flow period is considered. Figure 6.11 shows a recorder plot of the influent flow rate to the Goudkoppies plant over a two-day period. [Note that the chart is read from *right to left*]. In this case a heavy thunderstorm occurred over the major part of the collection area between 16h00 and 17h00 on the Friday; meteorological office records showed that approximately 75mm of rain fell in the collection area, making this one of the heaviest storms that occurred during the first 10 months of 1981. Comparison of the cyclic pattern for this day's flow with those of previous days indicated that (1) the patterns were almost identical up to 20h00 when the storm flow caused a deviation from the normal pattern; (2) the effect of the storm passed away relatively slowly - by approximately 02h00 on the Saturday the flow rate appeared to have returned to the normal pattern; and (3) the hydrograph of the storm flow pattern appears to be similar to that selected for the simulations, as shown in Fig 6.10.

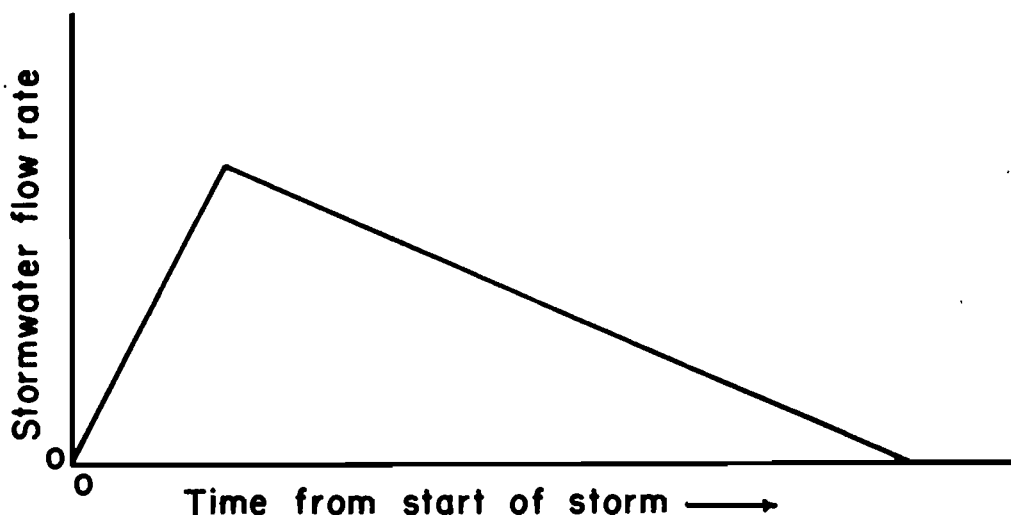


Fig 6.10 Form of storm flow pattern superimposed on usual influent flow rate pattern.

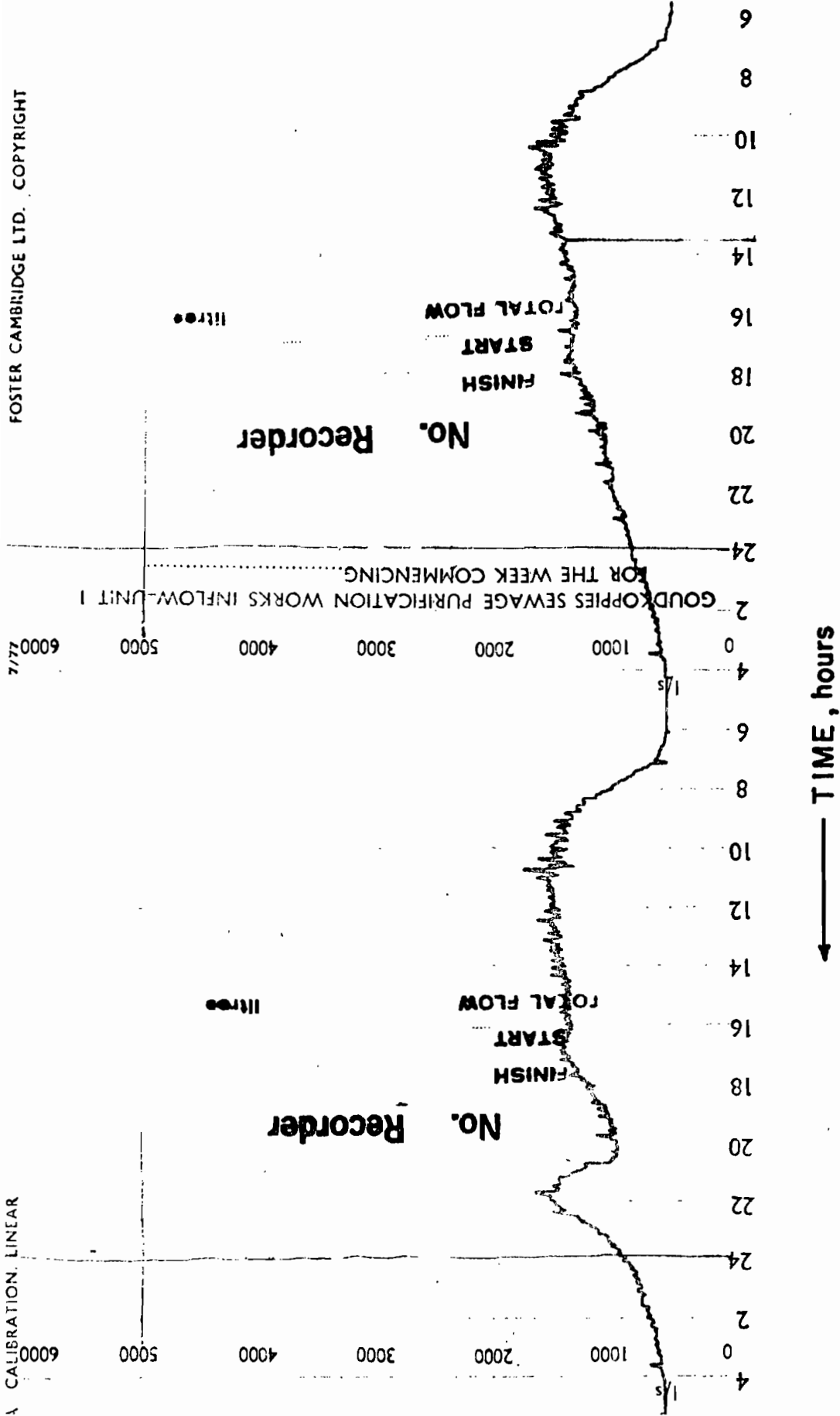


Fig 6.11 Example of the influence of ingress of storm water into the Goudkoppies WWTW wastewater collection sewers.

With regard to the effect of the storm flow on the influent concentration pattern, it would seem most likely that the action of the storm water entering the plant would be to reduce the concentration through dilution. However, because continuous monitoring of concentration is not included and the strategy has no means for quantifying the reduction, it is assumed that no change in the influent concentration pattern occurs. This assumption in no way influences the results presented later for showing how the strategy deals with the hydraulic shock - it will only cause the effluent load pattern to differ partially from that likely to be encountered in practice.

Once the form of the influent storm patterns is fixed, a second question must be answered; namely:

- (2) What will be the *magnitude* of the storm flow? The form of the influent storm flow pattern is shown in Fig 6.10; it is now necessary to quantify (a) the rates of increase and decrease of the storm flow rate, and (b) the peak storm flow rate. Selection of the magnitudes of these factors also is a subjective one; because of the difficulty in choosing these values appropriately it was decided to test the behaviour of the strategy under two sizes of storm input, with the rate of increase and decrease in storm flow rate being the same for each case. Details of the rates of change of flow rate, peak storm flow rate, etc., for the two storms (referred to as a "small" and a "big" storm) are listed in Table 6.2; units of flow are the same as used elsewhere i.e. 1 unit equals the normal mean daily inflow rate.
- (3) At what *time* of day will the storm flow commence? The time at which the storm flow enters a WWTP will depend on a number of factors; for example, time of day when a rainstorm in the collection area occurs, length of sewers, gradients of sewers, etc. To test the behaviour of the control strategy under storm flows in an adequate manner, it is necessary to consider two possible situations - one where the storm flow enters the

Table 6.2: Description of "small" and "big" storm flow patterns used in simulations.

Parameter	Small	Big
Rate of increase during rising flow (units/hour)	0,2	0,2
Rate of decrease during declining flow (units/hour)	0,04	0,04
Peak storm flow rate	0,4	0,8
Duration of rising flow rate (hours)	2	4
Duration of declining flow rate (hours)	10	20
Storm flow as a fraction of usual daily total inflow	0,1	0,4

plant when the tank level is dropping and approaching its minimum level, and one where the flow enters when the tank level is increasing, and approaching its maximum level. The two times selected for the commencement of storm flow are 04h00 and 16h00, respectively.

Having quantified the storm flow patterns it now remains to demonstrate the manner in which the control strategy will behave under these unusual inputs. The selection of the storm flow patterns requires the investigation of four different cases - a small and a big storm commencing at either 04h00 or at 16h00. For the simulations an in-line equalization tank with a 5,5 hour retention time (based on the normal mean daily inflow rate) is used. In order to exclude the possible interference of other factors, the daily influent wastewater patterns are taken as being very close to the historical patterns; each simulation covers a two-day period, with the storm commencing on the first day and the storm flow pattern being superimposed on the wastewater influent flow rate pattern.

3.2.1 Storms Commencing at 04h00

Previous simulations have shown that, under the usual inputs of flow rate and concentration encountered at the Cape Flats WWTP, tank hold-up is decreasing at 04h00; Figure 6.2 illustrates how the hold-up continues decreasing up to about 13h00 when a minimum is reached - with a 5,5 hour tank this minimum is close to the lower allowable hold-up limit of 5 percent. Figures 6.12 and 6.13 illustrate the controlled response of the equalization tank when a small and a big storm, respectively, commence at 04h00.

- (1) Small storm (Fig 6.12): The top section of the Figure shows how the small storm flow is superimposed on the usual input pattern; the storm flow increases up to 06h00 and thereafter falls off until the storm flow contribution is zero at 16h00. The results illustrate how the action of the strategy is to "spread out" the effect of the storm:

The strategy increases the outflow rate as the storm flow increases because there is no fore-knowledge as to when the peak will be reached; once the peak storm flow has passed and the actual inflow rate gradually returns to the historical pattern, the action of the strategy is to distribute the excess inflow over an extended period. The nett effect is that the tank effluent flow and load rate patterns are very similar to the optimal patterns.

Two features contribute to allow this behaviour: (1) the relatively small amount of excess flow entering the plant - the daily inflow is only increased 10 percent; and (2) the storm occurs at a suitable time in that hold-up capacity is available to store the excess flow - this is reflected in the difference between the tank hold-up profile for Day 1 and Day 2.

- (2) Big storm (Fig 6.13): The action of the strategy under the large input is very different from (1) above, because the daily inflow is 40 percent greater than usual and the effect of the storm persists for a full 24-hour period before influent

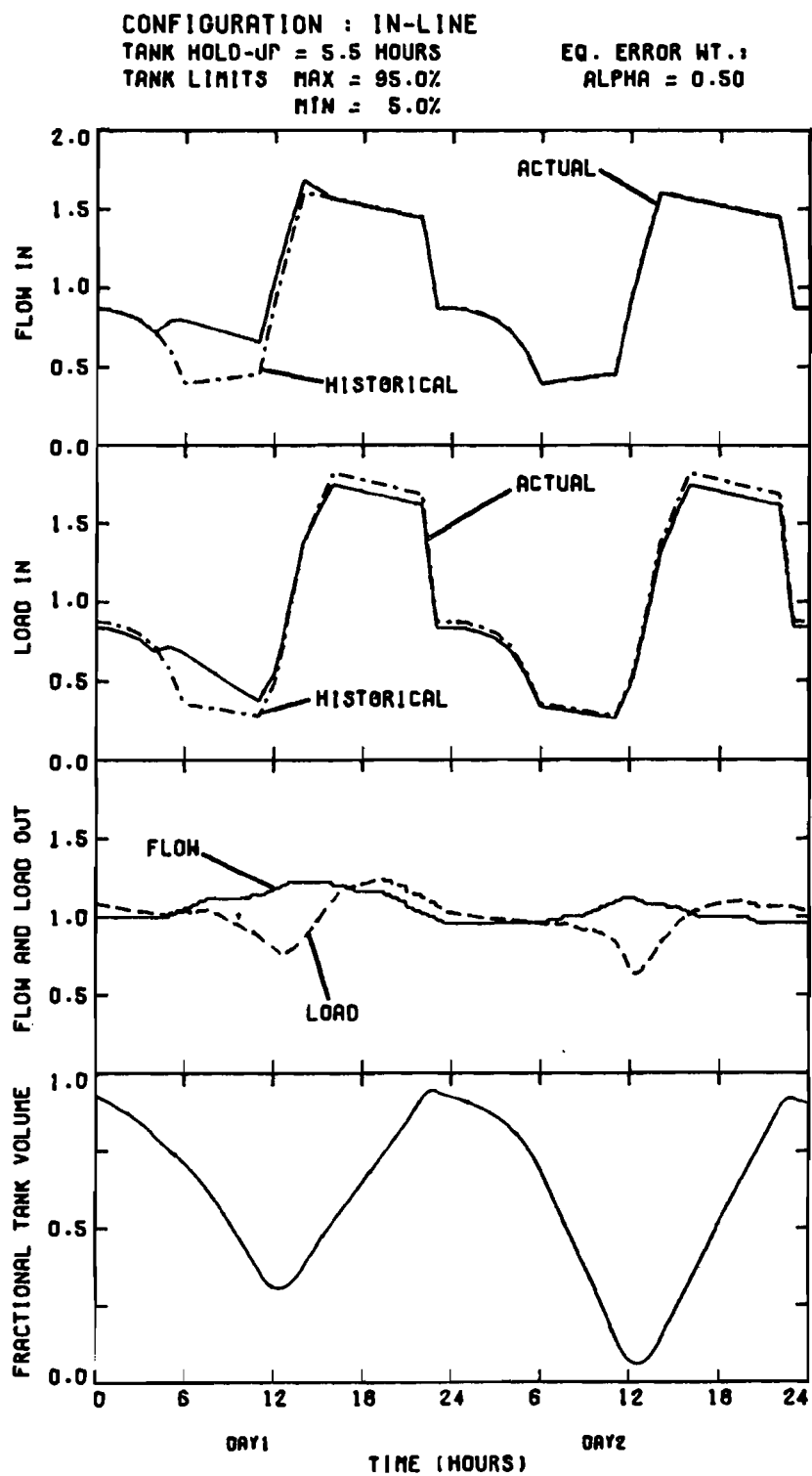


Fig 6.12 Strategy-controlled output of an equalization tank under a "small" storm input commencing at 04h00.

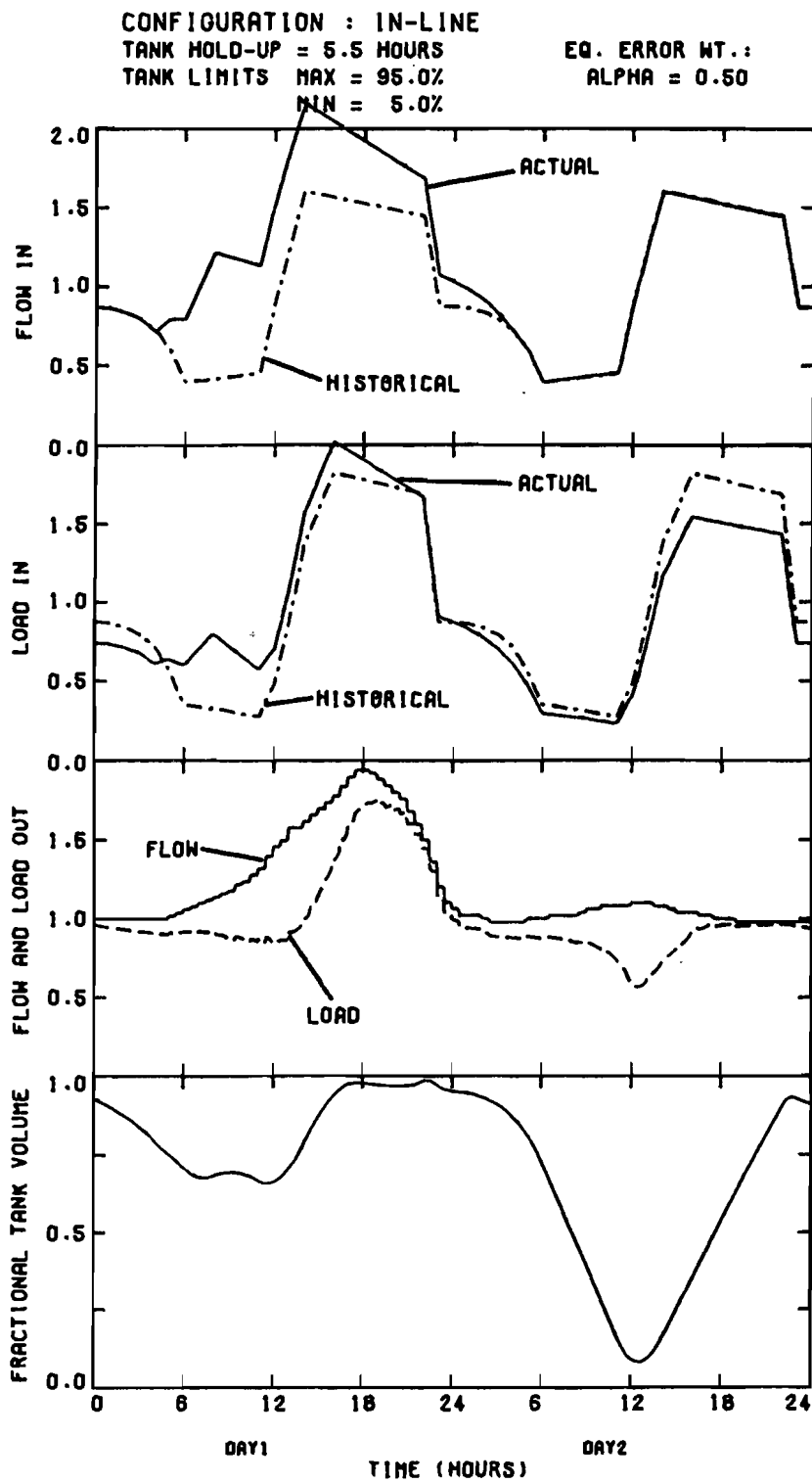


Fig 6.13 Strategy-controlled output of an equalization tank under a "large" storm input commencing at 04h00.

conditions return to normal. In this case, because the equalization facility is so over-loaded, the primary concern is to avoid overflowing the tank. Thus, although the storm flow passes its maximum at 08h00, it is necessary to continue increasing the outflow rate steadily up to 18h00. Thereafter, the outflow rate more or less follows the influent pattern until the tank effluent flow and load rates approach their respective mean values.

3.2.2 Storms Commencing at 16h00

Under normal operation the tank hold-up is increasing at 16h00; therefore it can be expected that storms starting at 16h00 will exert an even worse effect than storms starting at 04h00 because there is no longer excess capacity in the immediate future for storing additional flow. Figures 6.14 and 6.15 again illustrate the controlled response of the equalization facility under a small and big storm input, respectively, but this time for storms commencing at 16h00.

- (1) Small storm (Fig 6.14): In this case, even with the relatively small increase in flow rate, it is necessary to increase the tank outflow rate substantially to avoid overflowing the tank. Comparing these results with those of Fig 6.12 (same storm, but commencing at 04h00), near-optimal behaviour can be maintained only by distributing the excess flow over an extended period if the storm commences at a time when there will be available hold-up capacity in the future.
- (2) Big storm (Fig 6.15): With a big storm commencing at 16h00 the position is more aggravated; in fact, even though the tank outflow rate is raised to twice the normal value, the tank overflows slightly between 20h00 and 22h00. Once the actual influent flow rate drops towards the mean, however, the excess tank volume normally available during Day 2 is utilized to distribute the excess flow over a longer period.

3.2.3 Comments Regarding Performance Under Storm Inputs

A general conclusion from the simulations of the controlled response of an equalization tank under storm inputs is that, to maintain near-

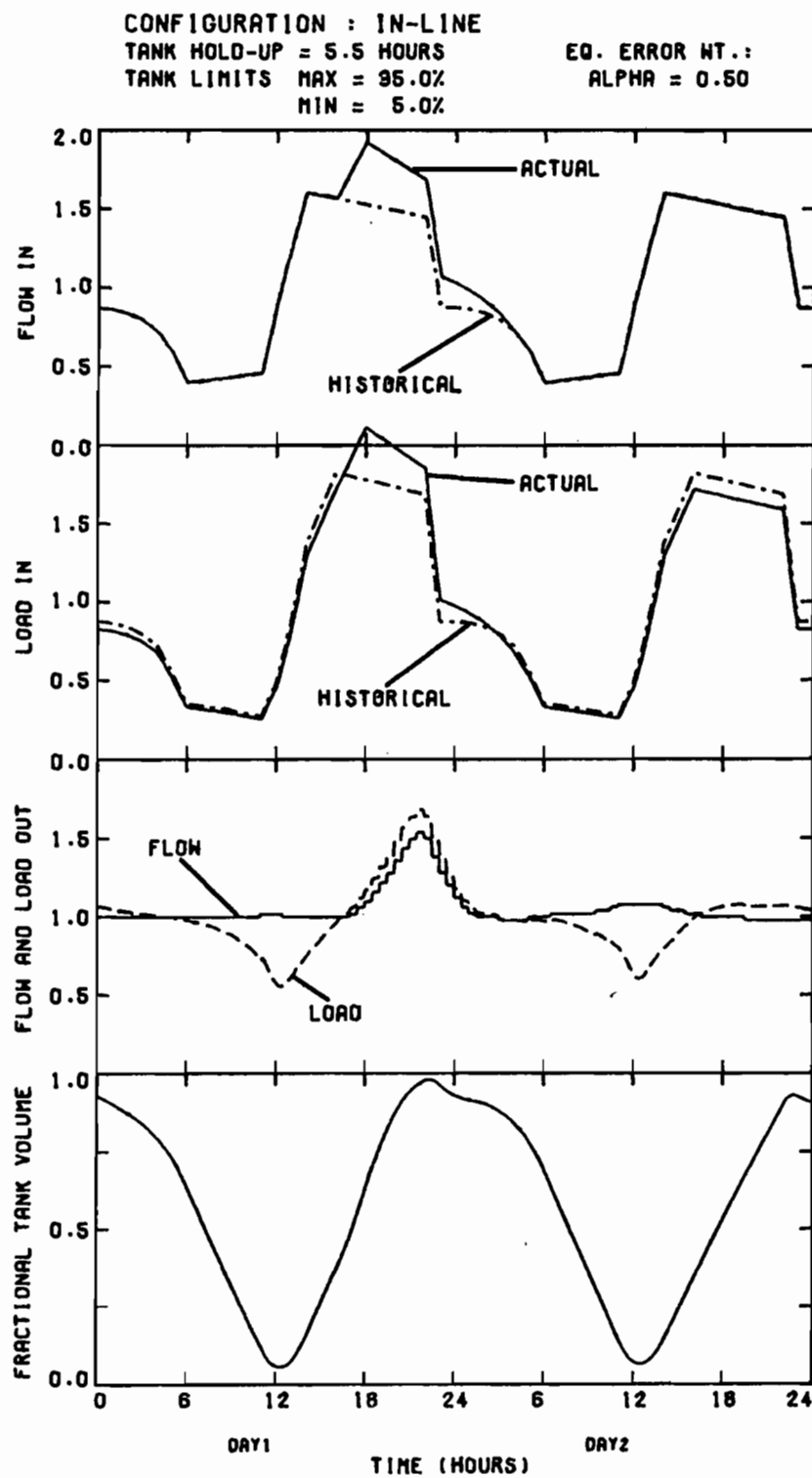


Fig 6.14 Strategy-controlled output of an equalization tank under a "small" storm input commencing at 16h00.

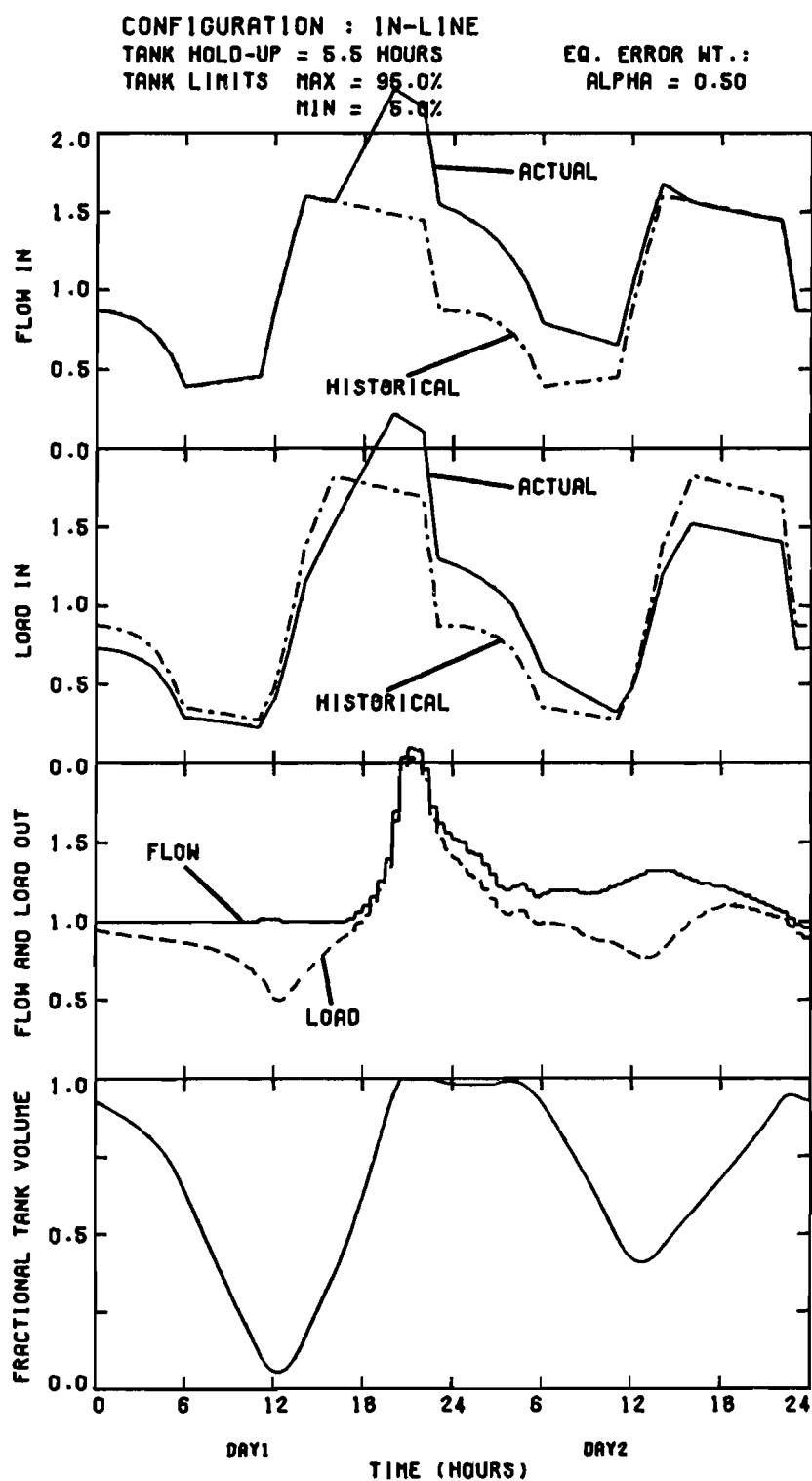


Fig 6.15 Strategy-controlled output of an equalization tank under a "large" storm input commencing at 16h00.

optimal operation on a continuous basis, excess tank hold-up capacity must always be available so as to enable excess flows to be stored and distributed over an extended period; the magnitude of storm which can be handled in this way will depend on the amount of available excess hold-up. One way to achieve this would be to use, say, an 8 hour retention time tank, and to specify the upper allowable tank hold-up limit as about 70 percent of the total. By suitable adjustment of the penalty error for volume limits in the error expression used by the equalization algorithm, such a system always would have the capacity to absorb relatively large shock loads. Also, under normal conditions the operating hold-up would be roughly equivalent to a 5,6 hour retention time tank and would lead to relatively good equalization of both flow and load under normal conditions. Under normal circumstances it is doubtful whether such a scheme would be worthwhile; in most cases shock loads large enough to over-load an equalization facility will occur very infrequently. It would seem more reasonable to use the available hold-up fully, accepting that upsets due to storm flows may occur, rather than setting aside capacity to deal with infrequent unusual inflows and thereby achieving a lesser degree of equalization than necessary for the major part of the year. However, each situation must be judged according to the circumstances prevailing at a particular plant. If, for example, over a part of the year, storms occur regularly, then a reduction in the upper hold-up limit can be specified for tank operation over that period, and/or the tank volume can be increased at the design stage.

The effect of storm flows through a plant can be particularly onerous on the secondary settling as this increases the mass flux throughput on the tank, and loss of sludge over the effluent weirs is a common occurrence at such times. A modification in the plant design can reduce this effect considerably: through a flow topping method divert the influent flow in excess of the maximum allowable flow to the process direct to the secondary settling tank. Although the flow through the settling tank is increased, the solids mass flux throughout is maintained near-constant, and the settling tank will behave more effectively.

4. SELECTION OF CONTROL INTERVAL LENGTH

In all the simulations of the controlled equalization tank performance presented in Chapter 5 and in this Chapter, control interval lengths of 30 minutes have been used. That is, at half-hourly intervals the equalization algorithm is used to determine the optimal outflow rate from the tank for the ensuing half-hour; except in cases where emergency control action is required, this flow rate is not changed during the half hour. This particular control interval length was selected purely on the basis of providing seemingly satisfactory results in the simulations.

To investigate the factors requiring consideration in the selection of the control interval length, additional simulations were carried out using a range of control interval lengths (15, 30 and 60 minutes) and for a range of tank retention times (3, 5 and 8 hours). These simulations identified one important feature regarding the selection of control interval length.

Irrespective of the tank retention time, there is a slight improvement in control strategy performance as the length of the control intervals is shortened; the extent of the improvement increases as (1) the magnitude of the deviations between the actual and historical influent flow rate patterns increases, and (2) as the retention time of the tank decreases.

This feature is best explained if one considers an example where, say, the actual inflow rate corresponds identically to the historical pattern up to a point and then, immediately after the outflow rate has been specified for an interval, the actual inflow rate suddenly becomes progressively larger than the historically-expected inflow rate. There will be a lag in the response of the control strategy in making any necessary adjustment to the tank outflow rate because the increased flow rate will be noticed only at the end of the control interval; this response time is obviously reduced if the length of the control interval is shortened. It was found that, for any tank size, as the intervals are shortened, the behaviour of the control strategy becomes more stable because differences between the actual and expected inputs

are picked up more quickly, thereby enabling small adjustments to be made at short intervals rather than having to make large changes at longer intervals - this latter behaviour may lead to overcompensating for certain fluctuations in the influent patterns.

The effect of changing control interval length was highlighted in the case of a 3 hour retention time tank. Because of the rapid response of the small tank it was found that, if control intervals of 60 minutes are used, the response of the strategy is hopelessly inadequate; problems are continually encountered with tank overflow and under-flow. However, as the control interval length is decreased from 60 to 30 and then to 15 minutes the operation of the control strategy improves markedly.

Rough guidelines for the selection of control interval lengths for different equalization tank sizes are listed in Table 6.3. It should be stressed that these values are not fixed; rather, because these values give satisfactory results in the simulations using the Cape Flats influent data, and because this influent data appears to be typical for a WWTP, it is likely that the same selection will be appropriate in other cases.

Table 6.3: Guidelines for selection of control interval lengths

Mean Tank Retention Time (Hours)	Control Interval Length (Minutes)
< 4,5	15
4,5 - 6,0	30
> 6,0	30/60

CHAPTER SEVEN

IMPLEMENTATION OF CONTROL STRATEGY AT FULL-SCALE

1. INTRODUCTION

Once the control strategy had been developed and tested by simulations of the controlled response of different equalization facilities under various input patterns of flow rate and concentration, the final phase in the project was the implementation of the control strategy at full-scale. The success, or failure, of this phase obviously constitutes the "acid test" for the control strategy - whether or not the favourable results obtained in the simulations can, in fact, also be achieved in practice.

An underlying feature in the *development* and *testing* of the control strategy was a continual effort to provide a means for controlling the operation of an equalization facility which (1) will result in optimal, or near-optimal, operation on a continuous basis, and (2) is suited for practical implementation.

Development: In the development a continual effort was made to structure the strategy in a manner suitable for the eventual practical implementation. This was achieved through taking cognizance of the instrumentation available for implementing the scheme, and structuring the strategy accordingly. For example, the direct measurement of inflow rate is circumvented by structuring the strategy to require only mean inflow rates over, say, half hour intervals - information which can be calculated from outflow rate and tank level change over the interval i.e. from information provided by instruments which in any case are necessary for the implementation.

Testing: During the testing phase of the control strategy, simulations of the controlled equalization facility response were performed using not only input data measured at full-scale WWTP's, but also a variety of input patterns selected

to stress the capacity of the control strategy. This enabled emergency control procedures requiring information on only the outflow rate and tank level to be incorporated in the strategy i.e. emergency procedures which are practicable.

In the transition from the simulation phase to that of implementing the strategy, one aspect in which problems were anticipated was allowing for the time required for application of the equalization algorithm at the beginning of a control interval i.e. a real-time limitation:

At the start of a control interval the tank outflow rate for that interval must be specified by the strategy. When testing the strategy by using simulated inputs as discussed in Chapters 5 and 6, real-time limitations were not of any consequence. Simulations of the controlled tank response, in fact, involve two separate simulations: firstly, the equalization algorithm must simulate the *expected* tank response under the expected inputs for an ensuing 24-hour cycle; and secondly, the computer program must simulate the *actual* tank response under the specified inputs, subject to the outflow rate determined from application of the algorithm. In testing the control strategy under specified input data, at the start of a control interval the algorithm is applied to determine the required tank outflow rate; once this value has been determined, only then does the program simulate the actual tank response for the duration of the control interval i.e. during application of the algorithm at the start of the interval time was, in effect, "frozen". However, in practice the extensive computation of the optimum tank outflow rate from application of the algorithm using a micro-computer may require a computation time of several minutes i.e. computation time may constitute a large fraction of the control interval. This is in conflict with the effective assumption in the simulations that the computation is instantaneous, or conversely, that the real world stops for

the duration of the calculation. For this reason it was necessary to re-structure the control strategy slightly; the means by which this was achieved is discussed later.

Once the development and testing of the general control strategy had been completed, permission was obtained from the City Council of Johannesburg to implement the strategy at the Goudkoppies plant. This particular plant was not the ideal one for testing the control strategy (the causes for this are discussed later), but despite these problems it was decided to use this plant for two reasons:

- The Goudkoppies equalization tank had been manually operated for a considerable time; consequently, data under manual operation was available for comparison with the microcomputer-controlled operation.
- The Goudkoppies equalization tank was the only one available; the only alternative would have been to test the strategy at pilot scale.

2. DESCRIPTION OF THE GOUDKOPPIES PLANT

The Goudkoppies Wastewater Treatment Plant is situated, on gently sloping ground, approximately 30 kilometers south-west of the Johannesburg city centre. The major source of wastewater for the plant is the central business district of Johannesburg, while the balance is of a domestic nature chiefly from the Orlando region of Soweto. The plant has been designed for a mean inflow rate of 150 Ml.d^{-1} and a mean raw influent COD concentration of $900 \text{ mg COD.l}^{-1}$. At present the plant is underloaded, with a mean daily inflow rate of between 90 and 110 Ml and a mean influent COD concentration of approximately $600 \text{ mg COD.l}^{-1}$. However, modifications to the sewer network, to be completed by late 1981, will raise the inflow to the design load of 150 Ml.d^{-1} ; the influent COD concentration is also expected to rise to approximately $800 \text{ mg COD.l}^{-1}$.

Figure 7.1 shows a schematic flowchart of the Goudkoppies plant; the actual layout of the plant can be seen in the aerial photograph in Fig 7.2.* At the header works the raw influent sewage is screened

* Fig 7.1 shows the flow from the equalization tank as passing to a single activated sludge module; the outflow from the tank is distributed between three identical activated sludge modules, each designed to handle a flow of 50 Ml.d^{-1} .

and degrittied; thereafter the flow passes to two clusters of circular primary settling tanks (four tanks in each cluster). The total underflow from the primary settling tanks constitutes only about 2 percent of the total inflow; this underflow is pumped to a sump from where it flows by gravity to anaerobic digesters at the nearby Klipspruit plant. Between 35 and 45 percent of the influent COD is removed at present in the primary settling tanks. Settled sewage flows, also by gravity, via two underground pipes, to the in-line equalization tank, entering the tank just above the base of the tank. There are three outlets from the equalization tank - one to each of the three activated sludge modules.*

The three activated sludge modules are identical and have been designed according to the five-stage Phoredox process, with the objective of removing both nitrogen and phosphorus from the influent. The influent, together with the underflow recycle from the secondary settling tanks, enters an anaerobic zone (2080 m^3) at the head of the process; from the anaerobic zone the flow passes sequentially to a primary anoxic zone (4800 m^3), an aeration reactor (14700 m^3), a secondary anoxic zone (4800 m^3), and a small re-aeration reactor (2700 m^3), and finally to the circular secondary settling tanks. An internal recycle transfers mixed liquor from the main aeration reactor to the primary anoxic zone.

A detailed discussion of the biological process does not fall within the framework of this investigation. The design of the equalization tank, however, is of importance and will be discussed in some detail.

2.1 Description of Goudkoppies Equalization Tank Construction and Operation

The Goudkoppies equalization tank, constructed of concrete, is set on a gentle slope between the primary settling tanks and the activated sludge modules so as to allow gravity flow to, and from, the tank. A detailed plan of the tank is shown in Fig 7.3. The tank is rectangular in plan with dimensions of 150m by 50m, and a vertical side wall depth of 3,8m. The overflow weirs are set 3,03m

* A fourth activated sludge module can be seen at the bottom of Fig 7.2. However, no mechanical equipment has been installed in this module and the module is not connected into the flow network.

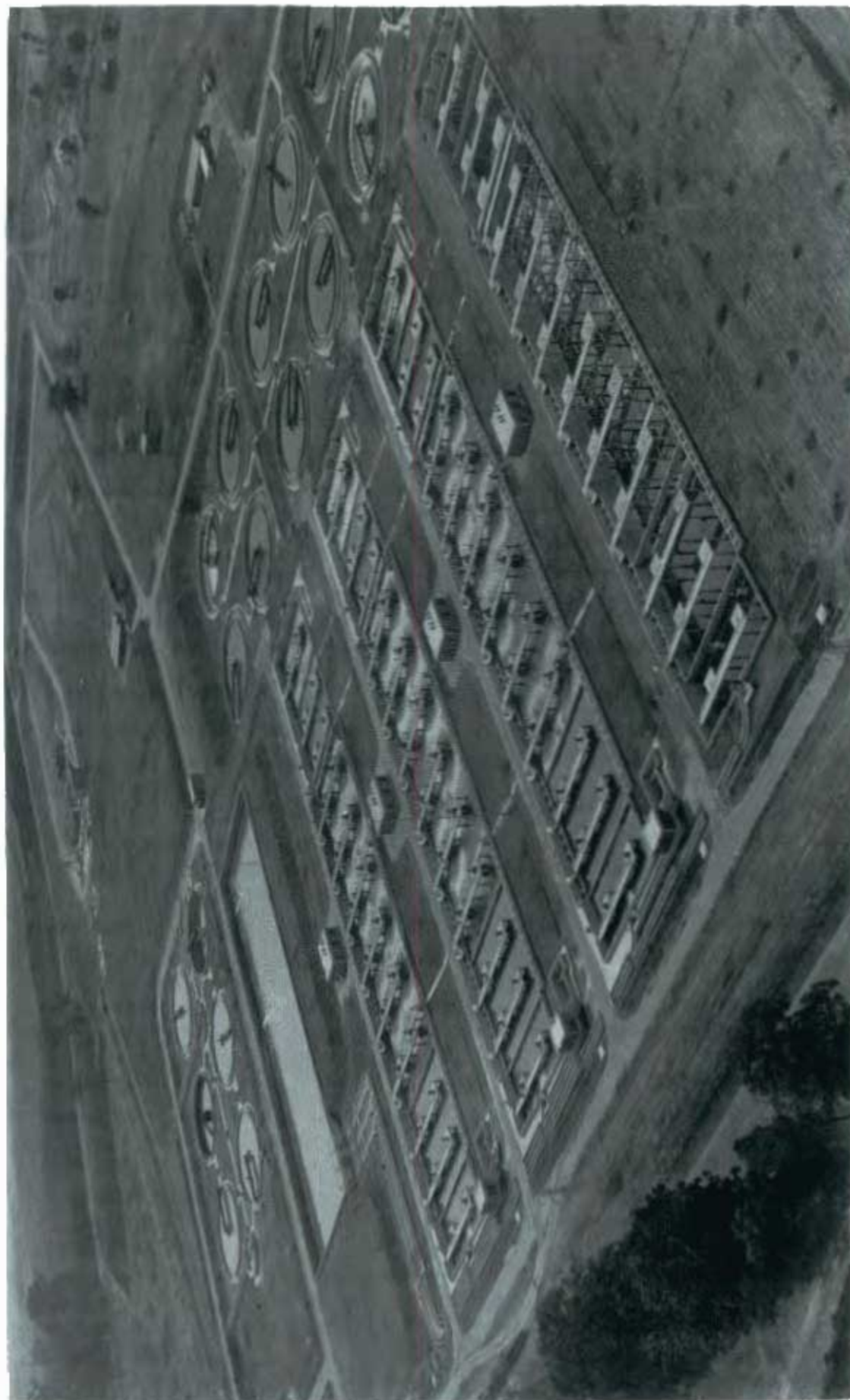


Fig 7.2: Aerial photograph of the Goudkoppies Wastewater Treatment Plant, Johannesburg. Raw influent sewage is screened and degrittied at the header works (at the top centre of the photo); thereafter the flow passes to the primary settling tanks (six can be seen in the photo although there are now eight tanks). Settled sewage flows via two pipes to the equalization tank and is distributed between the three operational activated sludge modules. The secondary settling tanks can be seen at the right centre of the photograph.

above the base of the tank, giving a tank hold-up capacity of 22750 m^3 . Based on the plant design flow, this hold-up corresponds to a mean tank retention time of $3,64$ hours; with the present flow the mean tank retention time is approximately $5,5$ hours. In terms of the results presented in Fig 4.7, Chapter 4, the present retention time should allow efficient equalization of both flow and load to be attained, with a marginal decrease in efficiency as the design flow is approached.

There are two inlets and three outlets from the tank. The relative positions of the inlets and outlets are indicated on the plan in Fig 7.3.

Inlets. Flow from the primary settling tanks enters the equalization tank via two large-diameter pipes just above the tank base; the two pipes are positioned 10m and 40m from a corner of the tank along one of the 150m side walls.

Outlets. Three identical outlets from the equalization tank are positioned at the corner of the tank furthest from the inlets. The outlets are immediately adjacent to one another and form an integral part of the 150m side wall. Detailed drawings of the outlet configuration are shown in Fig 7.4. The outlets are rectangular, and the outflow from each is set by the position of a motor-driven Rotorque gate valve. Each of the three streams leaving the tank enters a flow measuring flume; the flow rate through each flume is measured by measuring the depth of flow in the channel approximately 5m upstream of the flume using an air bubbler/pressure transducer instrument. The measured tank outflow rate through each of the flumes is displayed on the respective control panel (mounted on the tank wall) on a dial graduated in litres per second.

The outflow rate from each tank outlet is controlled by a feedback controller. The required outflow rate is determined by the position of a setpoint potentiometer located in the flow controller panel. The flow controller

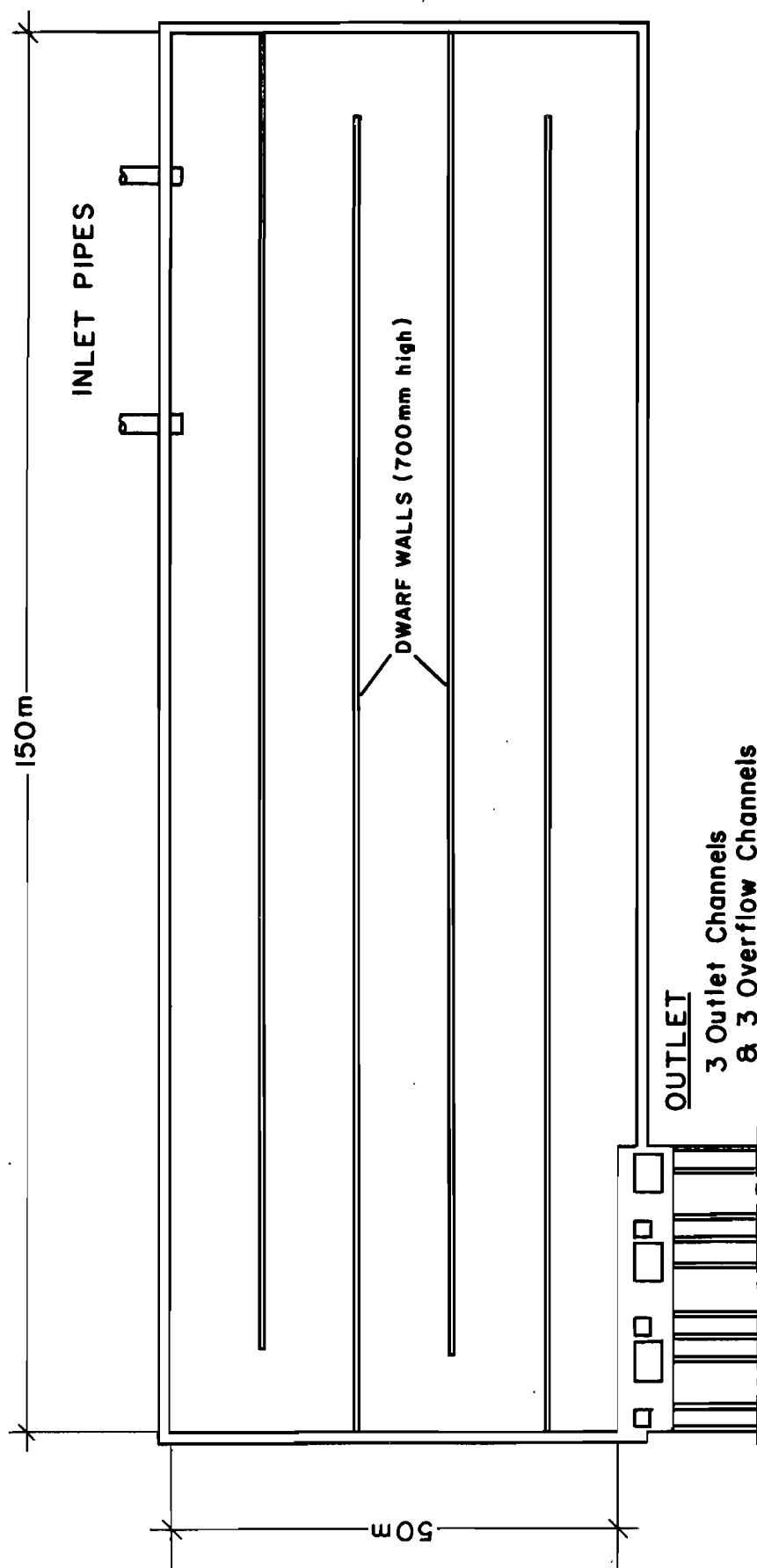
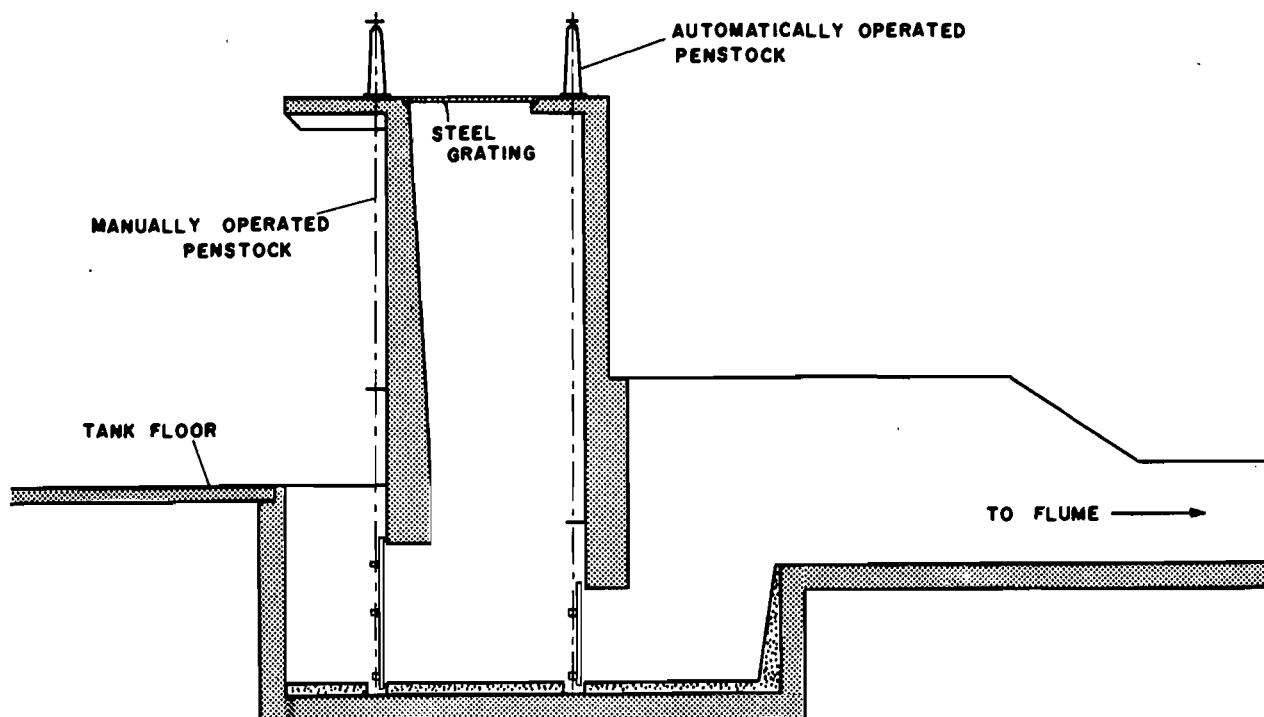


Fig 7.3 Plan of the Goudkoppies Wastewater Treatment Plant in in-line equalization tank.

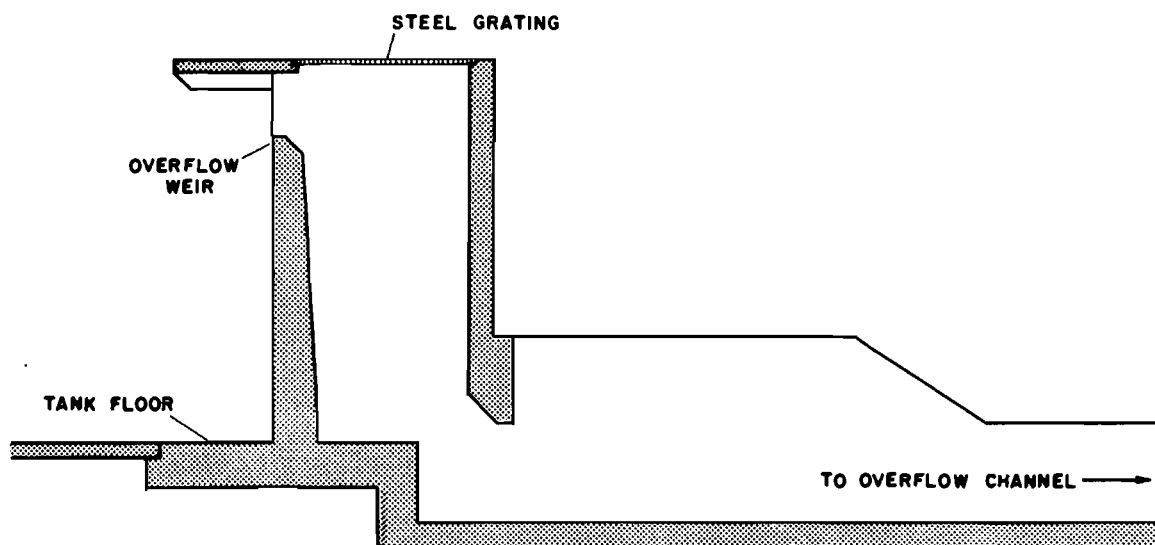
uses the output from the pressure transducer as a feedback signal, and if the flow rate exceeds certain limits from the setpoint value, a motor is actuated to change the position of the gate valve by an incremental amount so as to reduce the differential between the measured and the setpoint flow rate. The magnitude of the differential which causes the motor to be actuated is determined by the setting of a proportional band potentiometer in the flow controller circuitry. In order to provide stable control it is necessary that the proportional band setting is such that the differential which causes the gate position to be changed is larger than the change in flow rate which occurs when the gate is moved by an incremental amount; if this were otherwise the controller would "hunt". Therefore, with these flow controllers, the accuracy within which a specified outflow rate can be maintained is effectively determined by the minimum period over which the motor-drive can be activated - if this period is very short then fine adjustments to the outflow rate can be made, and the limits about the set point which if exceeded, cause the motor to be activated, can be made correspondingly small.* However, if only large adjustments are possible then the accuracy of the flow control is impaired because the flow rate necessarily must be allowed to fluctuate within an even larger range of the setpoint - if the limits causing the valve to move are too close the controller will "hunt".

Before implementing the control strategy the flow controllers were tested. The tests showed that there was cause for concern because the proportional band setting was such that the motor-driven valves were actuated only when the difference between the actual flow rate and the set-point exceeded about 150 l.s^{-1} - about a 30 percent indeterminacy considering that the usual outflow rate setting is in the region of 500 l.s^{-1} . The behaviour as a result of this is illustrated

*The size of the adjustments can also be decreased through changing either the structure of the outlet from the tank or through changing the gearing of the motor; however, both of these changes would be costly and were therefore discounted as possibilities.



(a) Outlet under normal flow conditions.



(b) Tank overflow outlet.

Fig 7.4 Drawing of the equalization tank outlet configuration for (a) normal outflow and (b) overflow.

in Fig 7.5 which shows a recorder plot of the flow rate from one tank outlet over 24 hours; although the specified outflow rate was 500l.s^{-1} the valve position was not altered over the day despite the variation in the actual flow rate between 330 and 560l.s^{-1} caused by head changes in the tank. [Between 17h00 and 21h00 the outflow rate remained constant because the tank was overflowing into a channel parallel to the measuring flume and the head in the tank was constant over this period]. This insensitivity was clearly unacceptable considering that the magnitude of the flow rate adjustments required by the control strategy would be about 2 percent of the usual flow rate. However, it was found that by fine-tuning the controllers and reducing to a minimum the period a motor-drive is actuated, the tank outflow rate could be held within approximately 5l.s^{-1} of the desired value i.e. within 1 percent accuracy.

Overflow weirs. In the event of the tank hold-up exceeding the maximum tank capacity of 22750m^3 , flow passes over three identical overflow weirs adjacent to the respective outlet gate valves (see Fig 7.4). Each overflow discharges into an open channel parallel to the respective flow-measuring flume, and joins the respective flow to the biological plant immediately downstream of the flume.

Three features appeared to contribute to the inefficient utilization of the Goudkoppies equalization tank while under manual control:

- The proportional band within which the flow could vary before the flow controllers were activated was too wide. This problem could have been remedied by reducing the period for which the motors driving the gate valves were actuated, and correspondingly reducing the proportional band setting.
- The operators experienced difficulties in making the correct estimates of the tank outflow rates, particularly in the transition from week to weekend, and *vice versa*, when there are significant, and fairly sudden, changes in both the

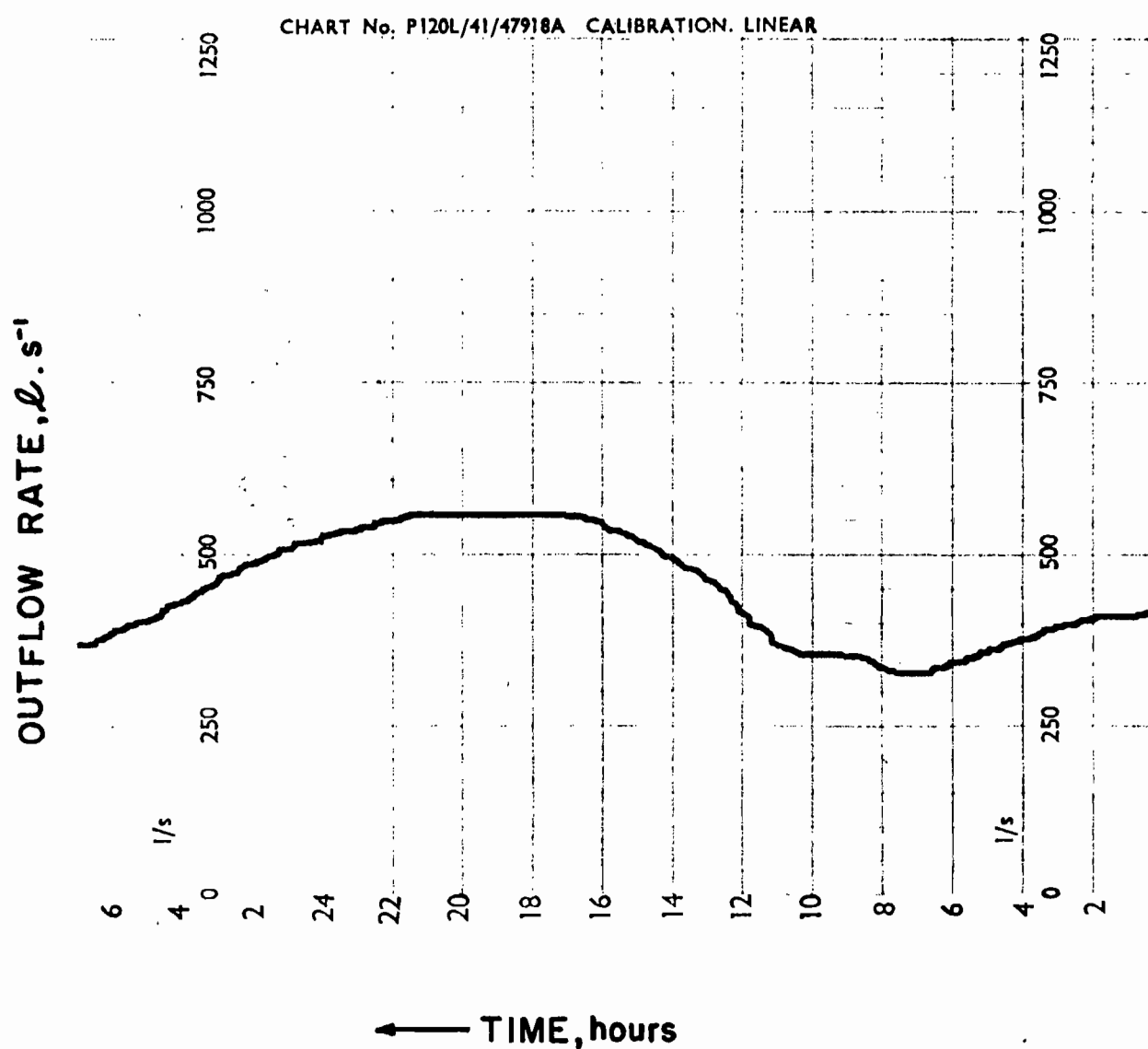


Fig 7.5 Example of 24 hour flow rate response in one tank outlet with a specified set point of 500 l.s^{-1} (Broad proportional band setting).

daily mass inputs of flow and load and their associated diurnal patterns.

- The tank contents were, and still are not, completely mixed. This feature was the major one causing problems in the operation of this equalization facility; this aspect merits further detailed discussion.

In the initial design of the equalization tank at Goudkoppies the objective was to achieve good *flow* equalization; load equalization was regarded as a secondary objective and provision for mixing of the tank contents was not included. As a result a large degree of settlement of particulate material on the base of the relatively shallow tank was anticipated. To prevent any accumulation of solids in the tank, a system of four 700 mm tall dwarf walls was constructed along the base of the tank as shown in Fig 7.3; by allowing the tank level to drop below 700 mm each day the flow would be canalized between the dwarf walls, thereby flushing out any solids each day and preventing any accumulation in the tank. However, if the tank is not drained each day in this fashion, solids rapidly accumulate on the tank floor; consequently when the tank level does drop below 700 mm a slug of material is flushed into the biological reactors and the COD concentration in the stream to the biological processes increases to as high as $6000 \text{ mgCOD.l}^{-1}$. To avoid this occurrence the tendency developed to specify the outflow rate controller set points to intentionally underestimate the required outflow rate, and accept that the tank would overflow for a portion of the day; in this way the operators ensured that the tank level never dropped low enough to flush solids from the tank. The result of this operating pattern not only negated, in part, the function of the equalization tank, i.e. the purpose of flow balancing, but also caused an increasing accumulation of solids in the tank which, at some time, would have to be removed. That the mass of solids in the tank is substantial under this mode of operation was evident from two observations:

- There was a mass loss of COD of approximately 20 percent between the tank influent and effluent.

- There appeared to be a high rate of anaerobic activity on the base of the tank; gas bubbles continuously rose to the surface over the whole extent of the tank.

It was envisaged that when implementing the equalization control strategy at Goudkoppies the accumulation of solids in the tank could be prevented automatically by specifying the lower allowable tank hold-up limit as, say, 400 mm to ensure flushing of the tank each day. That is, implementing the control strategy at this plant would have the effect of both (1) improved equalization of the flow, and (2) prevention of the accumulation of solids in the tank - a situation not achieved when the tank was operated under manual control. The principal disadvantage of implementing the strategy at Goudkoppies (with regard to testing the strategy) was that, because there was not efficient mixing of the tank contents, simultaneous flow and load equalization (incorporated in the strategy) could not be tested.* However, it was decided to accept this disadvantage, and to proceed with the implementation at the Goukkoppies plant.

3. EQUIPMENT REQUIREMENTS FOR IMPLEMENTATION OF CONTROL STRATEGY

The basic requirements for implementing the control strategy, in addition to a suitable microprocessor, have been identified in Section 3, Chapter 5; these are the facilities to:

- (1) Adjust the tank outflow rate from the microprocessor;
- (2) Measure the outflow rate and transfer this measurement to the microprocessor;
- (3) Measure the liquid level in the equalization tank and

* It would, of course, be possible to develop an empirical procedure for modelling the settlement, and subsequent flushing, of solids in the tank. A multitude of factors influence this behaviour; for example, tank dimensions, relative position of tank inlets and outlets, efficiency of primary settling tanks, etc. Because of the complexity of such a model it was decided that initially the approach would be to concentrate entirely on flow equalization, and thereafter to, perhaps, develop some empirical model to enable the incorporation of load equalization, depending on the resultant behaviour of the tank effluent load rate response.

transfer this measurement to the microprocessor.

To satisfy these requirements an interface must be included in the link between the microprocessor and the plant; this interface unit is needed to suitably condition the signals passing between the two items. A schematic representation of the equalization control strategy system is shown in Fig 7.6*.

Normally the development of such a system would be relatively quick as the majority of the electronic equipment can be purchased "off the shelf"; however, to reduce costs, a large portion of the equipment was developed, built and tested at the University of Cape Town. This resulted in a substantial saving, but caused a delay in the implementation. As it was necessary to reduce costs, this option

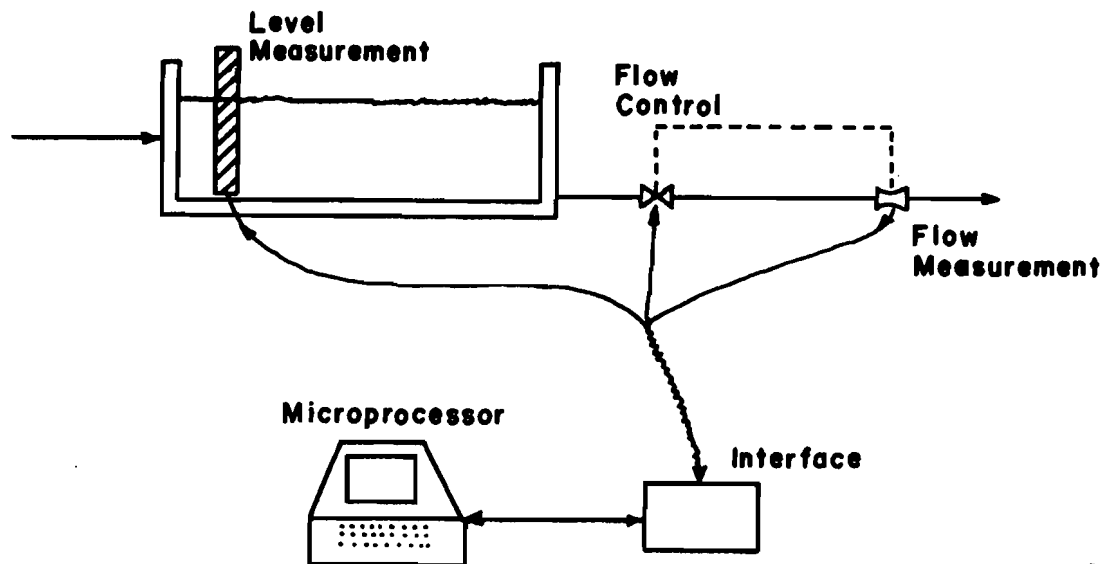


Fig 7.6 Schematic representation of requirements for implementing the control strategy.

* At the Goudkoppies plant there are three outlets from the tank; therefore provision must be made to control and to measure three outflow rates.

was the only one open. Generally, however, it could be accepted that it would be easier, perhaps, to use commercially built electronic modules where possible - this would make for easier maintenance of the equipment.

Five different aspects of the equipment and requirements for the implication of the control strategy at the Goudkoppies plant are now discussed in more detail; these are

1. The microprocessor
2. Measurement of the tank outflow rate
3. Setting the tank outflow rate
4. Measurement of liquid level in the tank
5. The interface unit

3.1 Microprocessor/Microcomputer

It has been stated previously that a "suitable" microprocessor is required for implementation of the control strategy. As yet the term "suitable" has not been qualified; in the discussion so far it has merely been assumed that the microprocessor will be able to carry out the range of tasks necessary for the implementation. The general characteristics of microprocessor control systems are now discussed briefly; this provides a basis for rationalizing the choice of the microprocessor system selected for this particular application.

It is a common misconception that a microprocessor is all that is needed to control a process or to do calculations. Firstly, to execute a program or to store data requires that the microprocessor should have access to a memory from which it can read instructions or data and to which it can write information. Secondly, control of a process using a microprocessor is possible only through outputting control signals to the process and retrieving information which reflects the status of the process; this means that the microprocessor must also have access to input and output elements. These requirements indicate that a microprocessor constitutes only one part of a microcomputer system used for process control. Dortmans

(1981) makes the following distinction between a microcomputer and a microprocessor:

"A microcomputer is the interconnected collection of microprocessor (CPU), memory and input/output (I/O) elements, while the microprocessor can be characterised as just the managing part of such a microcomputer (see Fig 7.7)".

Identification of the characteristics required from the microcomputer which is "suitable" for implementing the control strategy is best done through listing the general requirements for implementing the strategy as follows:

1. Extensive numerical computation capability for application of the equalization algorithm: the microcomputer must allow use of a high level language for writing the programs.
2. Input of process parameters and output of setpoints for the flow controllers on the plant: the minicomputer must provide easily available facilities for I/O.
3. Storage of both process data and computer programs. This facility can be provided by various hardware items; however, probably the most suitable item is a floppy disk as this facilitates development of the computer programs.
4. Speed of operation. The iterative equalization algorithm program must be executed sufficiently fast for the appropriate application of the control strategy. Two factors determine the speed of execution of a microcomputer program:

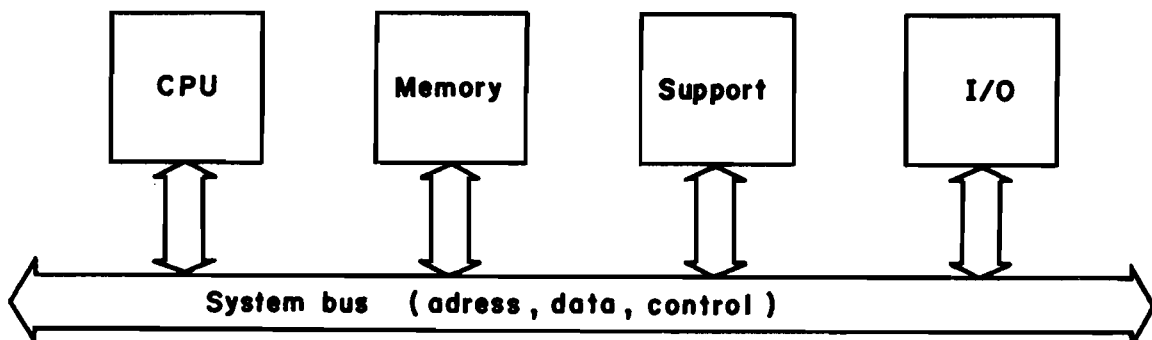


Fig 7.7 Structure of a microcomputer

- Nature of software. High level languages available for microprocessor applications are either of the interpretive type or the compiler type. With interpretive languages each line of source code is compiled as it is executed; these have the advantages that they generally are easy to use and editing of programs is simple. In the case of compiler language, a machine code version of the program is generated before execution; once the program has been compiled the machine code can be executed without referring back to the source code. The major advantage of compilers over interpreters is that the program is executed approximately 100 times faster.
- 8 or 16 bit processors. At present most microprocessors commonly encountered in control applications are either 8 or 16 bit machines; this refers to memory word size and the width of the data bus. Without going into detail, it suffices to note that the speed of a 16 bit microprocessor is tens of times faster than an 8 bit machine. The disadvantage of the 16 bit machine is that both the hardware and software is many times more expensive than for the 8 bit machine.

Selection of a suitable microcomputer for a particular application involves evaluation of a wide range of commercially available systems. The majority of small integrated systems (i.e. CPU, memory, VDU, disk, etc.) contain a PROM-resident BASIC interpreter which implies relatively slow execution of programs. Changing to a different language is only possible through changing the language card; this facility is only available in a restricted number of systems. Further disadvantages often encountered with these machines are - (1) software and compatible peripherals are only available from the manufacturers - this excludes the possibility of cost-savings through developing certain hardware items in-house; and (2) often the disk is only suitable for program storage and file handling facilities are limited. The system eventually selected as the most suitable for this application was the SWTP microcomputer which is based on the Motorola

6809 microprocessor. The features which make this machine particularly attractive for this application are:

Hardware flexibility. The approach with SWTP microcomputers is to supply a chassis containing power supplies, etc., and a motherboard which carries the various system buses. A series of modules are available to plug into the motherboard (e.g. CPU, memory). This allows a system to be assembled to meet the required specifications for a particular application. In addition to the main components there are additional ports specially set aside for I/O devices - these items can be purchased as standard units; however, specific devices can be designed and manufactured to operate from these locations. One particularly attractive feature of the system is that the eight available I/O slots (ports) are predecoded to 16 addresses per port; therefore, after a device is slotted into a certain physical position, the device resides at specified addresses in memory, allowing easy access from both high level language and assembler programs.

Software flexibility. There is a wide range of inexpensive software available for use with the SWTP microcomputer. For this particular application the following software packages were used:

FLEX^{*}: This is the Technical Systems Consultants (TSC) disk operating and file management system. The software has been designed specifically to operate on the SWTP machine and is probably the most widely used disk operating system for Motorola microprocessors. In addition to the disk operating system, FLEX has various other components which are also used in the development of software for implementation of the control strategy; these are the FLEX Mnemonic Assembler and the FLEX Text Editor. An additional advantage of the FLEX system is

* FLEX is the trademark of TSC and the copyright is obtained from TSC for the use of FLEX.

that a wide range of other FLEX-compatible software (e.g. high level languages) is available from other suppliers.

Pascal P-Code Compiler[†]: This is a high level language package which conforms to the standard Pascal format and which has been developed by LUCIDATA specifically to run under the control of FLEX. The code generated on compilation of a program is executed in conjunction with a run-time package; this approach gives execution times in the region of 50 to 100 times shorter than normally obtained with BASIC interpreters.

It is not necessary to discuss the specifications of the main system components (CPU, Memory, etc) in detail; this information is available in the various handbooks which describe the Motorola 6800/9 systems. However, it is necessary to supply certain information concerning the I/O devices as this will facilitate understanding of the computer programs presented in Section 4.

3.1.1 I/O Devices Linked to Microprocessor

There are four input/output (I/O) devices located in specific slots (or ports) on the SWTP motherboard. The common function of these items is to provide a means of communication for the microprocessor with the outside world. The ports at which the devices are located, and the range of 16 addresses in memory to which each port is decoded, are as follows:

<u>I/O Device</u>	<u>Port No.</u>	<u>Address Range</u> [*]
Serial Interface (ACIA)	0	\$E000 - \$E00F
Disk Controller	1	\$E010 - \$E01F
Analog to Digital Converter	3	\$E030 - \$E03F
Parallel Interface (PIA)	7	\$E070 - \$E07F

(1) Serial Interface (ACIA): The specific function of this device is to allow input and output of data to the terminal and printer.

[†] This package is available under licence from LUCIDATA Ltd.,
P O Box 128, Cambridge CB2 5EZ, United Kingdom.

^{*} The prefix \$ signifies a hexadecimal number.

(2) Disk Controller: This item provides for data exchange with the floppy disk drive.

(3) Analog-to-Digital Converter (ADC): The function of the ADC is to convert analog input signals (reflecting the status of the equalization tank level and outflow rates) to digital signals which can be used by the microcomputer control strategy program. The input signals are converted to the range 0,5 to 3,5 V (by the interface) and converted by the ADC to the equivalent binary value in the range 0 to 255; the ADC is capable of 8 bit resolution i.e. an accuracy of 1 part in 256, which was perfectly adequate for this application. The particular ADC is a 16 channel multiplexed device of which only four channels were used, for the three outflowrate measurements and one tank level measurement; these channels are located at addresses \$E030 to \$E033. To access information from the device a machine code program must be executed which will signal the device to read the required channel, after which the digital value can be obtained directly from the appropriate memory location mentioned above.

(4) Parallel Interface (PIA): The purpose of the PIA is to transfer digital information in and out of the system. The device used is based on the Motorola Peripheral Interface Adaptor which has two 8 bit parallel ports that can each be programmed either as inputs or as outputs. Once the device has been initialized (through executing a machine code program) each 8 bit port is treated as a single memory location with respect to read/write operations - each memory word therefore is able to convey 8 pieces (bits) of information (true or false). For the application at Goudkoppies one of the ports was initialized for input and the other for output; using this configuration it was (in conjunction with 4 external 8 bit latches) possible to convey all the required information to or from the microprocessor with a single PIA card. The specific functions of the inputs and outputs are as follows:

Inputs: The digital input information required by the control strategy program at various times during operation is (1) the status of 3 "day type" switches located on the front panel of the interface unit; and (2) the status of a binary counter

(clock) used for monitoring real time.

Day type switches: The control strategy requires to know whether the present day and the following one are either weekdays or weekend days; this information is needed by the equalization algorithm to set up historical influent flow rate profiles for an ensuing 24-hour cycle. The mechanism for providing this information is through each day manually setting three on/off switches designating "today", "tomorrow", and the "next day", respectively. For a weekday the appropriate switch is set in the "on" position, and in the "off" position for a weekend or public holiday. Depending on whether a switch indicates either a week day or a weekend day, either a 0 or a 1, respectively, is placed in specific bits of the 8 bit input word (bits 2, 3 and 4); the status of each switch is determined by executing a machine code program to sort out the information in the various bits of the word which resides at the location \$E072.

Clock counter: Implementation of the control strategy requires, *inter alia*, monitoring of real time. To do this the status of a 2 bit binary counter (which changes once a minute) is recorded in bits 0 and 1 of the input word located at \$E072 in memory i.e. the binary value in bits 0 and 1 changes at one minute intervals from 00 to 01 to 10 to 11, and back to 00, and so on. By executing a machine code program to read bits 0 and 1 of the input word at regular intervals, the actual time (in hours and minutes) can be appropriately updated in the software of the control strategy program (provided that the time is correctly initialized in the software at start-up). The reason for selecting a 2 bit binary counter will become apparent later when the structure of the control strategy program is discussed.

Outputs: The devices that are driven by the 8 bit digital output port are (1) three digital-to-analog converters (DAC's)

which provide the appropriate setpoint signals for the three tank outflow rate controllers; and (2) three "Local/Auto" control switches on the interface unit which indicate whether the tank outflow rate is to be set manually or from the microprocessor. The three DAC's each require input information in the form of an 8 bit word (a decimal value in the range 0 to 255 recorded in its binary form), while one bit is required to pass information to each of the three "Local/Auto" switches - in all 27 bits of information must be output from the PIA. As only a single 8 bit output port is available on the PIA card this port is connected to the inputs of four 8 bit latches. These latches, in turn, are connected to the DAC inputs and the three switches. In order to set the bit pattern on a specific DAC that bit pattern is written to the 8 bit output port of the PIA, and a strobe pulse to the specific latch is generated. The latch is thus set and remains in that status until reset.

3.1.2 Additional Circuitry Located in Computer Housing

Certain circuitry, in addition to the CPU, memory and four I/O devices, is located in the microcomputer housing. Although this circuitry is not directly linked to the computer bus system, and therefore does not constitute a component of the microcomputer, it was found to be most convenient if this circuitry is located in the computer housing. The circuitry for the three items in question is contained on a single PC board positioned in one of the vacant slots on the motherboard. The function of the different circuits is only described briefly here; detailed circuit diagrams are presented in Appendix D.

Four 8 bit latches: The function of these latches is detailed in the discussion of the PIA output port operation presented in Section 3.1.1.

Three DAC circuits: The function of the DAC's is to supply an analog signal which is conditioned by the interface unit to provide an appropriate setpoint signal for the three tank outflow rate controllers. The appropriate digital signals in the range 0 to 255 are transferred to the inputs of the DAC's;

these signals are then converted to analog signals in the range 0 to 5V for onward transmission to the flow controllers.

Clock circuit: The specifications for the clock require the status of a 2 bit binary counter to be changed at 1 minute intervals. This is conveniently achieved through a series of frequency dividers which suitably reduce a 2400 Hz signal derived from the microprocessor BAUD rate generator.

3.1.3 Summary of Data Transmission Functions.

At this point it is useful to summarize the information regarding the various data transmission functions described in Sections 3.1.1 and 3.1.2. This summary not only facilitates understanding of the hardware required for implementation of the control strategy at the Goudkoppies plant, but also forms a useful reference when discussing the various computer programs presented in Section 4. Figure 7.8 shows a block diagram of all the I/O facilities between the microprocessor and the outside world.

3.2 Measurement of Tank Outflow Rate.

Sewage leaving the equalization tank flows by gravity in open channels, of rectangular section, to the biological processes; common air bubbler/pressure transducer systems are used to measure the flow rates of the three streams leaving the tank. The primary element in each of the flow measuring schemes is a Parshall flume located approximately 20 m downstream from the tank; the flume restricts the width of the open channel along which the flow passes, causing the upstream level to rise. A bubbler system constitutes the secondary element in the scheme. A constant flow of air is forced through a dip tube fixed to the side-wall of the open channel 5 m upstream of the flume; bubbles of air escape from the open end of the dip tube at the base of the channel, and the back pressure on the tube is monitored. This back pressure is proportional to the immersed depth of the dip tube, and therefore to the liquid level in the channel.

The relationship between the flow rate in the channel and the depth of flow is non-linear and is given by the following equation:

$$Q = 1163,5 h^{1,5} \quad (6.1)$$

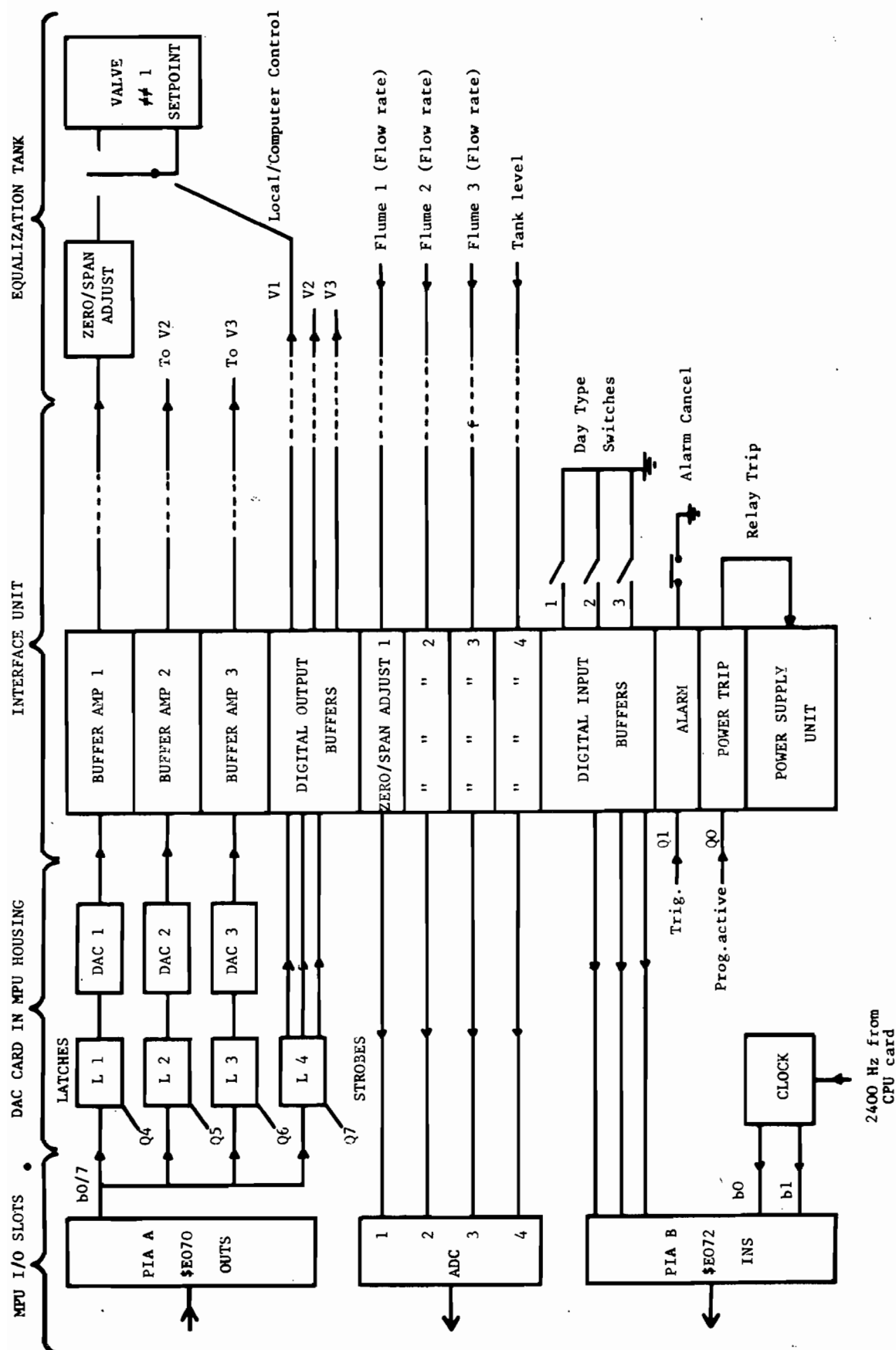


Fig 7.8 Block diagram summarizing data transmission functions.

where

Q = tank outflow rate, l.s^{-1}

h = depth of flow in channel, m

The maximum depth of flow which can be handled by each channel before spillage over the side walls of the flume occurs is 0,712 m - a flow rate of 700 l.s^{-1} . A pressure transducer is calibrated to supply the outflow rate controller with a feedback signal which varies from 7,5 V to 8,5 V (a 1 volt swing) as the flow rate increases from 0 to 700 l.s^{-1} .

In addition to being used by the flow controller, the voltage output from the pressure transducer is also transferred to the interface unit. At the interface the signal is conditioned to give a voltage signal in the range 0,5 to 3,5 V which can be interpreted by the analog-to-digital converter (ADC) located in the microprocessor unit; in this way the microprocessor can obtain measurements of the three outflow rates as required.

3.3 Setting the Tank Outflow Rate

The equalization algorithm resident in the microprocessor specifies the required optimum outflow rate from each of the three tank outlets at regular intervals. The process initially tested for setting these outflow rates was virtually the reverse of the procedure for measuring the outflow: when the outflow rate is to be set, the digital-to-analog converter (DAC) located in the microprocessor housing, outputs a voltage signal in the range 0 to 5 V to the interface unit. This signal is conditioned to give a second signal in the range 7,5 V to 8,5 V, depending on the required outflow rate; the second signal then becomes the setpoint for the outflow rate controller. This approach, however, gave certain problems with regard to obtaining accurate outflow rate settings for the following reason:

The required outflow rate from each tank outlet is usually in the region of 500 l.s^{-1} ; from Eq (6.1) it is apparent that when the flow rate is in the range 400 to 600 l.s^{-1} a small inaccuracy in the DAC output leads to a relatively large inaccuracy in outflow rate setting. Furthermore, it

was found that the DAC output tended to fluctuate very slowly from day to day; even though these fluctuations were very small, problems were encountered in maintaining the required outflow rate accurately on a continuous basis.

In contrast to the DAC, it was found that the outputs from the pressure transducers used to measure the three outflow rates were particularly stable. This stable signal, which ensures accurate flow measurements, was used to develop a second method for maintaining the outflow rate very close to the required value. The approach was as follows:

On starting-up the control strategy, the method initially tested is used to specify a setpoint for the flow controller only at the beginning of the first control interval. Thereafter, at regular intervals, the actual outflow rate is measured and compared to the required outflow rate stored in the microprocessor memory; if there is a difference of more than, say, 5 l.s^{-1} between these values a slight adjustment is made to the current setpoint signal from the DAC. In this way, even though the DAC output may fluctuate slightly from day to day, the required outflow rate always can be maintained very accurately. It was also found that because the changes in outflow rate, from one control interval to the next, are usually very small, the same method can be used to make these changes.

3.4 Measurement of Liquid Level in the Tank

Operation of the control strategy requires, in addition to measurement of the tank outflow rate, measurement of the liquid level in the equalization tank at any instant. Various instruments such as ultrasonic level sensors were considered for this application; although such instruments are neat and compact, and relatively easy to install, it was decided to use a more cumbersome float unit as this provided the lowest cost alternative.

The float unit was attached to the inside wall of the equalization tank, close to the three outlets from the tank, as shown in Fig 7.9. The unit consists of a float, attached to a steel tape, moving up

and down in a vertically-mounted 318 mm diameter PVC Class 4 stilling tube which is 3870 mm long; the dimensions of the float unit are shown in Fig 7.10. The bottom of the tube, which is open, is positioned 330 mm from the tank base. The float has a total travel of 2750 mm and can move over a range from 350 mm to 3100 mm relative to the base of the tank; in terms of the depth of the tank from base to overflow this corresponds to a hold-up range of 11,7 to 103,3 percent. It was found that if the tank level dropped to less than 450 mm the flow rate past the base of the stilling tube caused the level inside the tube to rise and fall, leading to slightly unstable readings. This behaviour was unlikely to cause problems in operation, however, because the tank level would seldom drop to less than 500 mm; it was found that if the tank level dropped below 500 mm then the head in the tank could not maintain the required flow rate through the outlets - for this reason the lower allowable tank hold-up limit is always selected as about 18 percent of the total tank depth (540 mm).

A signal indicating the position of the float, and thus the liquid level in the tank, is supplied by a potentiometer arrangement mounted on top of the stilling tube. As the float moves up or down, a steel tape attached to the float is either taken up or paid out from a wheel at the top of the tube. As the wheel rotates the potentiometer setting is changed to give an output voltage signal which varies over the range 0 to 5 V as the float moves from one extreme position to the other. This signal is transmitted to the microprocessor via the interface unit; knowing the dimensions of the float unit i.e. the length of steel tape), this signal can be interpreted as a tank hold-up for use by the microprocessor.

The only maintenance of the float unit appears to be occasional sluicing of the inside wall of the stilling tube, at about 4 month intervals, to prevent any build-up of crust which may hinder the movement of the float.

3.5 Interface Unit

In this Section the various *functions* of the interface unit are

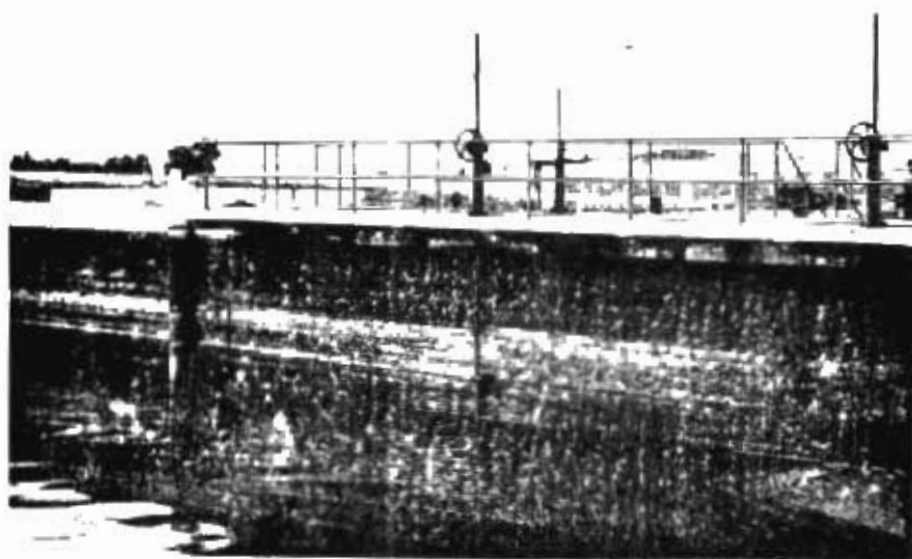


Fig 7.9: Photograph showing location of float unit adjacent to tank outlets.

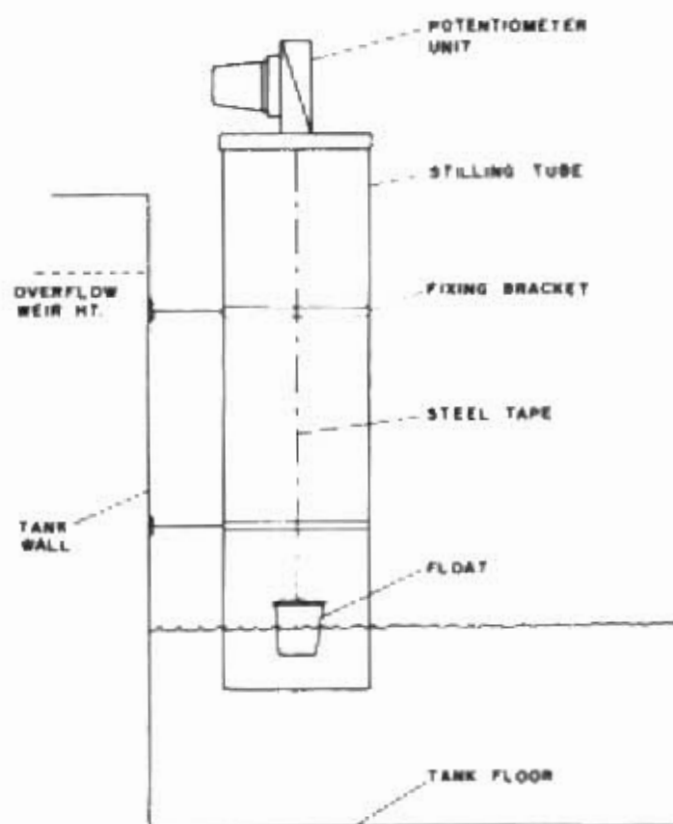


Fig 7.10: Schematic diagram of float unit.

discussed. No detailed documentation of the circuitry is presented here; the purpose, rather, is to explain the functions of the different circuits in more general terms. Detailed circuit diagrams are supplied for reference purposes in Appendix D.

The primary function of the interface unit is to suitably condition the signals passing between the microprocessor and the plant. These signals reflect (1) the liquid level in the equalization tank, and (2) the flow rates from the three tank outlets, and specify (3) the setpoints for the three flow controllers on the tank outlets. Although it is standard industrial practice to transmit analog control signals as current loops (e.g. 4 - 20 mA), in this application all signals are transmitted as voltages on twisted pair cables. This method was selected to fit in most easily with the existing instrumentation on the plant, and necessitated the minimum modifications to the flow controller circuitry, i.e. the least cost alternative. To prevent possible problems of interference or "noise" being picked up on the lines, in all cases the control voltages are fed into the inputs of differential amplifiers; in this way any interference, which is likely to be common to both lines of the twisted pair, is rejected. This scheme for the transmission of signals was found to give good results in the application.

The block diagram in Fig 7.11 shows the direction of transmission of the various signals, together with the different voltage ranges along different sections of the link between the microprocessor and plant. Conditioning of the three different categories of signal is now considered:

Setpoints for the flow controllers. The output from the three DAC's are signals in the range 0 - 5 V. These signals must be conditioned to give appropriate voltages in the range 7,5 V to 8,5 V at the flow controller setpoints. This conditioning of each signal takes place in two stages:

- (1) The 0 - 5 V signal is passed (without modification) through a buffer amplifier located in the interface unit to offer some isolation between cables to the

plant and the DAC circuitry. The buffer amplifier also drives a meter located on the front panel of the interface unit to supply a visual indication of the specified outflow rate (as a percentage of the maximum outflow rate of 700 l.s^{-1}).

- (2) The second stage in the conditioning is a zero/span adjustment circuit located in the flow controller panel. This circuit has an input differential amplifier as mentioned previously and two further amplifiers to appropriately shift the zero and adjust the range of the 0-5 V signal to a 7,5-8,5 V signal for the flow controller setpoint.

Flow rate signals. The three flow controller circuits each provide a signal in the range 7,5-8,5 V reflecting the depth of flow, and thus the flow rate, in the channels upstream of Parshall flumes at the three tank outlets. Each signal is passed to the input of a differential amplifier located in the interface unit- thereafter two additional amplifiers are used for zero/span adjustment to provide the appropriate signal in the range 0,5-3,5 V for input to the ADC.

Tank level signal. The output signal from the float unit is conditioned in an almost identical manner to that for the flow measurement signals, the only difference being that the output signal from the float unit varies in the range 0-5 V, as opposed to a range of 7,5-8,5 V for the flow controllers.

The interface unit provides the location for several other circuits for implementation of the control strategy; these are:

Digital inputs to PIA (see Section 3.1.1): Three circuits for the three day-type switches mounted on the interface panel each consist of a buffer to present the PIA 8 bit input port with a standard logic level (i.e. 0 or 1) on the selected bits.

Digital outputs from PIA (see Section 3.1.1): Whether or not

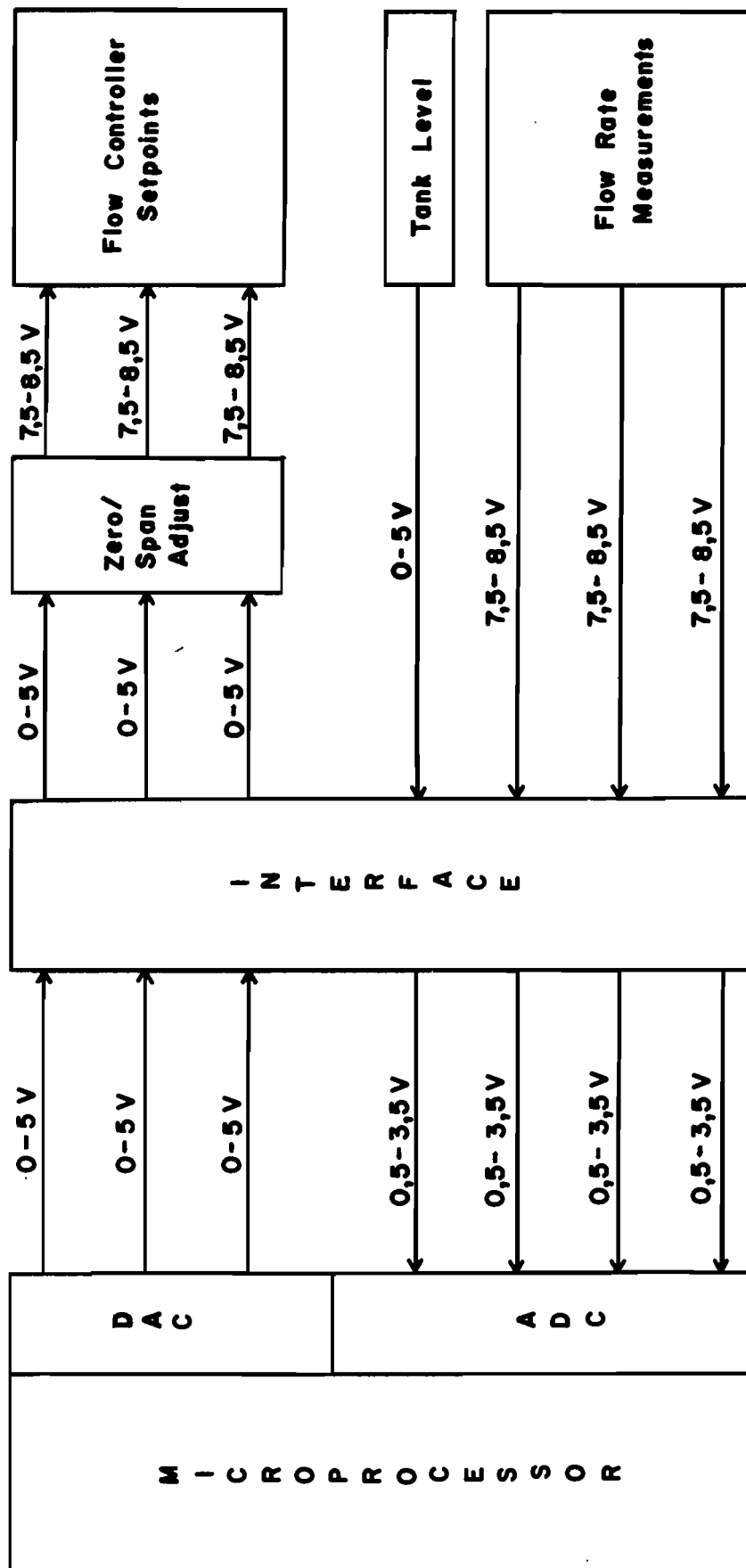


Fig 7.11 Transmission of signals between plant and microprocessor, via interface unit.

the three tank outflow rates are to be controlled from the microprocessor is determined by the status of three digital outputs from the PIA. The PIA signal is amplified to provide a switch closure output. This relay output enables the software to specify either that the flow controller accepts the microprocessor-generated setpoint or that the manually-specified setpoint is used. When the outflow rates are controlled from the microprocessor three LED's on the interface panel light up.

Two additional circuits housed in the interface unit relate to detection and prevention of errors that may occur during operation:

Alarm circuit. In the event of certain unusual behaviour (specified later), software will cause an audible alarm to be triggered. This draws the operator's attention to an error message printed on the VDU of the terminal. The alarm may be cancelled by a button on the interface panel.

Power trip circuit. During normal operation a "program active" pulse is generated at approximately 5 second intervals. If this pulse is absent for more than 30 seconds the circuit will be tripped, removing power from the entire interface unit, and the system will revert to the manually-specified setpoints on the flow controllers. This ensures fail-safe operation in the event of either a computer malfunction or a power failure; in either case it will be necessary to re-initialize operation of the control strategy.

4. REAL-TIME MICROPROCESSOR PROGRAM

The operation of the equalization facility, when under the control of the microprocessor, is directed by a single computer program which runs continuously. The function of this program is to carry out, and schedule, all the different operations necessary for the implementation of the control strategy in the real-time situation. For the particular application at Goudkoppies, a Pascal programming package was used for the mainline program. This package has been developed specifically for the Motorola 6800 series microprocessors,

and includes certain features which facilitate the development of the control program. These features become evident in the discussion below.

To develop the computer program for the real-time implementation of the control strategy it is necessary first to define the various requirements for the implementation; once these have been listed it becomes a simple matter to describe the development of the computer program which directs the operation. The basic requirements for the operation can be listed as follows:

- Monitoring of a clock. Certain procedures must necessarily be carried out at specific times; therefore, the micro-processor must maintain a continuous check on the actual time of day to enable scheduling of different events.
- Computation of the optimum tank outflow rate *at regular intervals*, and computation of the distribution of this flow between the three tank outlets. This involves utilization of the equalization algorithm, taking into account the immediate past behaviour of the equalization tank.
- Setting the outflow rates from the three tank outlets.
- Measuring the three tank outflow rates. This is necessary to supply information for both (1) updating historical influent flow rate data stored in the microprocessor memory for use by the equalization algorithm, and (2) maintaining a check on the actual outflow rates so that possible adjustments to the flow controller setpoints can be made.
- Monitoring the liquid level in the equalization tank. This information is required for (1) use by the equalization algorithm, (2) computation of actual mean inflow rates over each control interval for updating the historical influent data, and (3) maintaining a check on the hold-up situation in case of the possible need for emergency control action.
- Output of information concerning the operation of both the equalization tank and the control strategy either on a regular basis or when called for by an operator.

The requirements listed above demand mechanisms for communication between the control strategy program resident in the micro-processor and the "outside world". Two specific cases are involved:

- Output to, or receipt of signals from the interface unit which provides the link with the plant; and
- The facility to interrupt the normal operation of the microprocessor to access certain information with regard to either the operation of the control strategy or, more likely, the situation of the equalization tank at any instant. This facility applies specifically to information which is not output by the microprocessor on a regular basis.

Transmission of information to or from the plant. The method by which signals (reflecting outflow rates and tank hold-up, and signals for the flow controller setpoints) are transmitted between the microprocessor and the plant, via the interface unit, has already been discussed. Instruments on the plant form one end of this link, while the other end comprises *either* the output ports of the digital-to-analog converters (for signals directed to the plant - setpoint signals) *or* the input ports of the analog-to-digital converter (for signals directed to the microprocessor - the various measurement signals). So far there has been no discussion on how this information is either written to the DAC or read from the ADC; it has merely been stated that this requires execution of a machine code program. Consider, say, the case of writing information to the DAC:

At particular times the mainline Pascal program will require the outflow rate from the tank to be set; the version of Pascal used here allows a scaled value of the flow rate in the range 0 to 255 (for the range of possible flow rates of 0 to 700 l.s^{-1}) to be placed in a specific location in the microprocessor memory which is specially set aside for the use of the DAC (through the POKE command). However, to convert the digital information to a corresponding voltage signal on the output of the DAC for transmission to the flow controller setpoint, requires execution of a particular

machine code program. This is readily accomplished through the USER command in the mainline Pascal program as follows:

The USER command diverts execution from the Pascal program to the start address of the machine code program which has been located in a vacant area in the microprocessor memory. Once this machine code program has been serviced, the microprocessor returns to the Pascal program.

The DAC write program is one of a number of machine code programs which are resident in the microprocessor together with the mainline Pascal program. Details of the different machine code programs are presented in Section 4.2.

Operator interruption of program execution. The microprocessor runs continuously, either executing the mainline Pascal program or servicing one of the machine code programs. However, some mechanism is required to allow interruption of the processing so that the microprocessor can be instructed to output certain information which is not supplied on a regular basis. For example, an operator may wish to know what the tank hold-up is at a particular time; it should be possible to instruct the microprocessor to output this information.* The mechanism to do this is provided through the interrupt facility of the microprocessor, and again involves directing execution to a machine code program. In this way requests for information typed in from the keyboard can be processed. Details of the possible output and workings of this machine code program are presented in Sections 4.1 and 4.2.

The discussion above identifies two types of program for the implementation of the control strategy:

- A mainline program (written in Pascal language) which not only computes the optimal tank outflow rate profile, but

*The primary functions in the control strategy operation are (1) application of the equalization algorithm to determine optimum tank outflow rate settings at regular intervals, and (2) execution of certain procedures at specific times. It is necessary, therefore, to structure the computer programs in a manner such that operator interruption of program execution does not interfere with control strategy operation; this aspect of program structuring is detailed

directs the operation of the control strategy.

- A series of machine code programs which are accessed by the mainline program or from the keyboard.

These various programs are now discussed in detail. The approach here is to explain the function of different sections of these programs, rather than presenting actual software listings. Detailed listings of the programs are presented in Appendix E; these serve as a reference for the discussion which follows.

4.1 Mainline Pascal Computer Program

Individual functions of the mainline program have been listed at the start of Section 4, where the computational requirements for the real-time implementation of the control strategy are identified. Writing the software for each individual aspect in the particular version of Pascal used in this application does not pose any problem; a large part of this essentially involves translating the FORTRAN programs already written for the simulation study, with some small modifications. There are, of course, other sections required for the output of results specific to the Goudkoppies application; however, each entity again involved writing a simple Pascal program.

The main difficulty in developing the real-time program is to link all the subsections of program together while still ensuring that all the individual events are correctly sequenced. By this we mean that certain actions must be taken at specific times in order to operate the plant appropriately; it is the function of the mainline program to ensure that the necessary action is taken at the correct time and in the correct sequence. The importance of this aspect is best illustrated by an example:

Assume, say, that the tank level must be monitored at 5 minute intervals to check whether or not any emergency control action is required to prevent the level dropping below some specified limit. Assume also that the computation of the optimum tank outflow rate by the equalization algorithm has just commenced. This computation involves an extensive iterative procedure and may require an execution

time of, say, 10 minutes. It is apparent that during this 10 minute period the attention of the microprocessor cannot be directed exclusively to the determination of the optimum tank outflow rate; the microprocessor, amongst other functions, must monitor the liquid level in the tank at least twice, and perhaps carry out other procedures on the basis of these readings.

The problem of setting up the mainline program therefore is one of sharing, in some way, the facilities of the microprocessor so that each function is serviced, and yet without neglecting to carry out the various control operations at their specific times. The solution to this problem is through the structuring of the mainline program. The approach used here is to structure the program in a manner that allows application of a form of time-sharing system in which:

- Each program section that requires processing only receives the attention of the microprocessor for one or two seconds at a spell, even though the total processing time for a particular section of program may be several minutes.
- Real-time is monitored at intervals of a few seconds so that the attention of the microprocessor can be diverted to servicing time-specific functions within a few seconds, at most, of the required time.

This system, in effect, allows parallel processing of a number of different items, one of which is monitoring of a real-time clock. Structuring of the mainline program to incorporate this time-sharing system is achieved through the use of a series of software flags, as follows: Each sub-section of program for each of the individual functions (or requirements) of the control strategy is written as a separate Pascal procedure (or subroutine); these procedures are linked into a continuous program loop. At any time whether or not a procedure requires processing is indicated by the status of a flag associated with that particular procedure - if the flag is set (FLAG=1) then the procedure is processed for a maximum period of

about 2 seconds before re-entering the program loop; if the flag is not set (FLAG=0) then the next flag in the loop is scanned, and so on. In this way, by progressively moving around the continuous program loop several different procedures can be processed in parallel. At any one time it is unlikely that more than two or three procedures will require simultaneous processing; therefore, each "revolution" of the program loop will take, at most, about 6 seconds. By monitoring the clock once during each cycle, the status of the flags governing entry to the procedures for the time-specific functions can be changed within a few seconds of the required time, and then, during the next "revolution", the procedure for the particular function can be serviced - this leads to delays of only a few seconds in executing time-specific procedures.

Figure 7.12 shows the schematic structure of the mainline program, together with the names of the different Pascal procedures attached to the program loop.* On starting up the control strategy the first action is to initialize the control procedure (read in data, initialize program arrays, etc.); once this is completed, operation involves moving around the program loop continuously, servicing the various functions necessary for application of the control strategy, until execution is stopped either from within the program or through, for example, a power failure. Figure 7.12 only represents the structure of the mainline program, and in no way reflects the flow-chart of the real-time operation of the control strategy; in fact, the ordering of procedures around the program loop can be completely random - the sequence of performing different functions is determined solely by the sequence in which the status of the various software flags is changed. For example, if in Procedure A the flag governing entry to Procedure D is changed from 0 to 1, then Procedure D will be processed before Procedure A can possibly be re-entered - care must just be taken to re-set flags at the appropriate points to avoid confusion.

* An additional benefit of this method of structuring the program is that adjustments to the software can be made with a minimum of difficulty; additional procedures can be added to the loop (or removed) as completely independent units - only minor changes with respect to the procedure's software flag are required in the remainder of the program.

It was found that this approach to structuring the mainline program leads to satisfactory, stable operation of the control strategy. Although there is a delay of a few seconds in carrying out certain operations, this does not pose a problem because the response of the system being controlled (the tank) is relatively slow.

Having presented the overall structure of the control program, details of the function of the individual components are now discussed more fully. The sixteen different procedures linked to the program loop (see Fig 7.12) can be divided into four categories:

- (1) Procedures relating to the direct use of the equalization algorithm;
- (2) Procedures for output of information;
- (3) Procedures for scheduling the time-dependent events, and for other "bookkeeping" functions.
- (4) Procedures relating to the distribution of the total tank outflow between the three tank outlets.

4.1.1 Incorporation of Equalization Algorithm in Real-time Program

The primary problem with incorporating the equalization algorithm in a real-time control strategy arises from the relatively long calculation time required by the microprocessor to apply the lengthy iterative procedure for determining the optimum outflow rate from the tank - a problem which did not arise in the simulations of the control strategy behaviour (Chapter 6). In the case of the simulations it was assumed that application of the algorithm at the start of a control interval was instantaneous (or equivalently, that real-time was "frozen" for the period during which the algorithm is utilized); that is, the optimal tank outflow rate for a control interval was known at the start of the interval. However, in the practical implementation this assumption is no longer valid. Consider the situation at the beginning of a control interval when the tank outflow rate for the duration of the interval must be determined:

If, say, computation time for applying the equalization

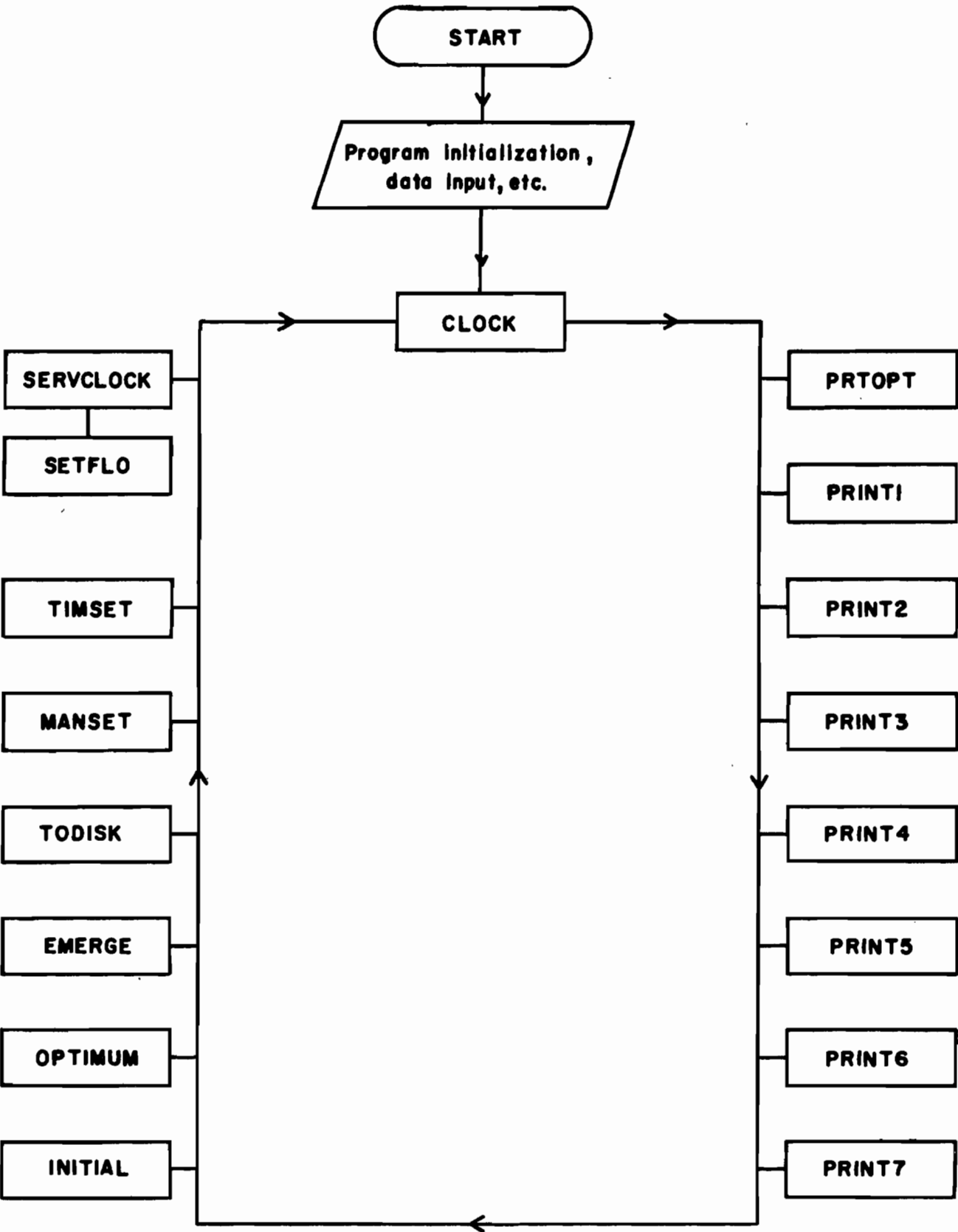


Fig 7.12 Structure of the mainline Pascal computer program.

algorithm is about 10 seconds, the short delay in setting the outflow rate would be acceptable, most probably, as this would be short compared to the response time of the flow controllers on the tank outlet. However, by trial it was found that the particular microprocessor used in this application would require between 2 and 10 minutes for these calculations, depending on (1) the number of adjustments necessary to determine the optimum 24-hour outflow profile, and (2) the length of the control intervals. For a specified control interval length the duration of this calculation can be shortened only through using a faster microprocessor; however, this alternative was unacceptable due to the extra cost. It was necessary therefore to investigate methods for accommodating the relatively slow application of the equalization algorithm.

One possibility would be to accept that there will be a delay in setting the optimum outflow rate for an interval. That is, initiate calculation of the optimum outflow rate at the start of an interval without adjusting the outflow rate setting from the previous interval; then, when the optimum value has been calculated, adjust the outflow rate to the optimum. A disadvantage with this approach is caused by the variable length of the delay in specifying the outflow rate; this leads to added complexities in those sections of the program used for determining actual inflow rates for the updating of historical data stored in the microprocessor memory. To avoid this added complexity it was necessary to investigate alternative approaches for incorporating the equalization algorithm in the control strategy which would not lead to a marked loss in optimality, but which would allow the outflow rate for a control interval to be set at the start of the interval. Two methods which would allow the outflow rate to be set at the start of a control interval are:

Method 1: From the start of one control interval commence the calculation of the optimal outflow rate for the *next* control interval; this will allow sufficient time to complete the computation. Then, at the end of the present interval, set the outflow rate for the *next*

interval, and commence with the calculation for the following interval, and so on. This approach results in a slight loss in optimality because it is implicitly assumed that the actual inflow rate during the interval in which the computation is made exactly equals that expected by the microprocessor; most likely there will be a slight difference between these two values. The loss in optimality can be reduced by reducing the length of the control intervals. There is a lower limit, however, to the length of the intervals because as the 24-hour cycle is subdivided into shorter intervals the amount of calculation increases correspondingly.

Method 2: A second approach which possibly can overcome the problem of increasing computation time with decreasing control interval length is to subdivide only the first control interval in the ensuing 24-hour cycle. This has the advantage over Method 1 that the loss in optimality is reduced by reducing the delay between determining the outflow rate and applying this value.

A number of approaches similar to the two set down above can be suggested - all with the purpose of being able to specify the tank outflow rate immediately at the start of a control interval. However, before initiating an extensive investigation into the different methods, it was decided to test the first approach in simulations as a guide-line to whether the method would be suitable in practice. The results of these simulations showed that, even when control interval lengths as great as 1 hour are used, there is only a slight loss in the level of performance. The only instances where problems appear to arise are when there is a large difference between the actual and the expected inflow rates when the tank level is close to the upper or lower hold-up limits. However, with half-hour control intervals, input patterns of a most unusual character are required to upset control strategy performance. For this reason it was decided to accept this approach in the full-scale implementation on an initial basis - it could always be replaced or modified at a later stage if unsatisfactory.

To summarize, the method for determining the optimal tank outflow rate is as follows:

Step 1:

At the start of a control interval the tank hold-up is measured, and, according to the expected inflow rate and the specified outflow rate (determined previously) over the present interval, the *expected* tank hold-up at the start of the next interval is calculated.

Step 2:

Set up the expected influent flow rate profile and an initial outflow rate profile for the 24 hours starting at the beginning of the next control interval.

Step 3:

Apply the equalization algorithm in the normal manner during the present control interval to determine the optimum outflow rate profile for the 24-hour cycle under consideration.

Step 4:

Accept the value in the optimal profile corresponding to the next control interval as the outflow rate setting to be used for that interval.

Implementing the sequence set out above for applying the equalization algorithm involves two calculation phases. At the start of a control interval the equalization algorithm must be initialized; thereafter, the iterative procedure for determining the optimum outflow rate profile is followed until any adjustment to the outflow rate profile no longer leads to a reduction in the value of the error expression. In order to be compatible with the method for structuring the main-line Pascal program, the equalization algorithm is 'split into two procedures, INITIAL and OPTIMUM, for the two phases identified above. Whether or not program control is diverted to these procedures during normal operation is controlled by the status of the flags FLAGIO (for INITIAL) and FLAGII (for OPTIMUM). Immediately prior to the start of a new control interval both of these flags are set equal to zero i.e. neither procedure is being processed. At the start of the control interval the status of FLAGIO is changed to 1 so that, in the next "revolution" of the program loop the procedure INITIAL is

processed; this involves (1) calculating the mean inflow rate over the previous interval, (2) updating the historical inflow rate data, (3) determining the expected 24-hour inflow rate profile from the start of the following control interval, and (4) initializing the various arrays for use by the equalization algorithm. The final step in Procedure INITIAL is to open Procedure OPTIMUM for processing (by setting FLAGII = 1) and closing INITIAL (by setting FLAGIO = 0). Thereafter, in subsequent "revolutions" of the program loop, Procedure OPTIMUM is processed for a period of about 2 seconds at a time; each computation spell involves a single adjustment of the tank outflow rate profile used by equalization algorithm at only one of the improvement intervals. This process continues until the optimum profile has been established, and may involve diverting execution to Procedure OPTIMUM several hundred times. At this point the *total* tank outflow rate setting for the next control interval is stored for later use, and Procedure OPTIMUM is closed i.e. FLAGII = 0, and only re-opened during the next control interval.

4.1.2 Printed Output of Results Provided During Operation

A large portion of the mainline Pascal program is made up of a number of procedures for the printed output of results during operation. In fact, these procedures comprise more than 30 percent of the total number of lines in the Pascal program. Eight output procedures are included in the overall mainline program structure in the usual manner i.e. each procedure is only processed when the status of the particular flag governing entry to the procedure is changed from 0 to 1 (see Fig 7.12). The output procedures, together with a description of the information supplied by each, are:

PRTOPT:

A list of the information which can be directed to output, as well as certain functions accessible through the keyboard interrupt facility (discussed in Section 4.2.1 later).

PRINT1:

A short list of process information such as effective mean tank retention time (based on mean historical daily inflow

*Examples of the actual printed output are presented in Appendix E.

rate and actual tank volume), allowable tank hold-up limits, equalization algorithm error expression weighting factors, etc.

PRINT2:

Historical inflow rate data stored in the microprocessor memory. The output consists of two columns of inflow rate data, one for the weekday pattern and one for the weekend pattern. The listed values are the mean historical inflow rates for each control interval in the 24-hour cycle.

PRINT3:

Actual results for last 24 hours. Once a day (at 07h45 here) the actual outflow rate settings for the three tank outlets over each control interval during the past 24-hours is printed. Values of the actual tank hold-up (as a percentage of the total) at the start of each control interval, as well as the actual mean inflow rates over the intervals, are also listed.

PRINT4:

Expected results for the ensuing 24-hour cycle. A printout is produced of the expected inflow rate and expected optimum outflow rate, and the expected tank hold-up at the start of each control interval, for the ensuing 24-hour cycle (starting with the next control interval).

PRINT5:

Level sensor reading. The tank hold-up (as a percentage of the total) is printed on request.

PRINT6.

Present error distribution. The procedure lists the values of the different error components, and the total, calculated by the equalization algorithm. Information regarding the number of cycles of adjustments to the outflow rate profile made by the algorithm is also provided. Normally this information would be of little interest to the plant operator; this optional output was only included to provide a check on

the control strategy behaviour in the development.

PRINT7:

Actual and requested outflow rates. The outflow rate settings specified for each of the three tank outlets and the actual measured outflow rates can be printed to provide a check on the functioning of the outflow rate controllers. Each of the three sets of values will most probably differ by a few litres per second, depending on the accuracy of the controllers in maintaining the correct required value.

A temptation in setting up a microprocessor-based control strategy is to print out reams of information at regular short intervals. While this approach may be impressive, it is unlikely that much of the information is ever useful; in fact, this approach can have a detrimental effect - providing lists of information are continuously being produced, a tendency on the part of the operator would be to automatically assume that the control strategy is functioning appropriately. The approach used here is to restrict the regular output of information to a minimum, and to provide the operator with a schedule of outputs required daily; by supplying guide-lines for assessing this output, a check on control strategy performance can be maintained.

Only one of the eight sets of information is printed on a regular basis; this is a listing of results for the past 24 hours which is printed each day at 07h45 by the Procedure PRINT3. In this case the status of FLAG3 is automatically changed from 0 to 1 by the software clock procedure at 07h45 each day. The remaining output information is only supplied on request from the keyboard, using the interrupt facility of the microprocessor. This involves changing the status of the software flag governing entry to the required procedure through initiating execution of one of the machine code programs (discussed later).

A final comment regarding the output of results is that certain of the printing procedures must be processed in short segments so as not to upset the time-sharing structure of the mainline program. This is necessary because printing time for some of the information on the relatively slow line printer used here can be up to 2 minutes.

This is achieved in the following manner:

On requesting particular output, the status of the appropriate flag is changed from 0 to 1. When that subroutine is encountered in the program loop only, say, 5 lines of the output are printed (requiring about 2 seconds) before returning to the program loop (without re-setting the flag to 0). In subsequent "revolutions" another 5 lines are printed at a time until the output is completed; at this point the flag is re-set to 0 before returning to the program loop.

4.1.3 Scheduling of Time-Dependent Functions

The mainline program is made up of a number of separate procedures (or subroutines) all linked to a continuous program loop. Control of the different procedures is through software flags which, if set to 1, allow execution of a particular procedure or, if set to 0, cause the procedure to be disregarded. The status of the flags must be changed in a particular sequence, and at appropriate times, from within the mainline program so as to correctly schedule the different functions required for application of the control strategy. The manner in which the status of the flags is controlled will now be considered.

On starting the control strategy one of the features of the initialization performed before entering the continuous program loop is setting all the procedure flags to zero, with the exception of FLAG8 for the procedure TIMSET which is set to 1; therefore, TIMSET will be the first procedure executed in the loop.* The function of TIMSET is to

- Prompt for the correct time of day from the keyboard to set the software clock.
- Initialize the hardware clock so that, in subsequent "revolutions" of the program loop, the software clock is correctly updated.

* The status of FLAG8 can also be changed from the keyboard through an interrupt; this allows the software clock to be checked and/or changed at any time.

- Set FLAG10 = 1 to open Procedure INITIAL so that calculation of the optimum tank outflow rate for the next control interval is started.
- Initialize some program counters (according to the time of day) so that various arrays of data used in the program can be appropriately ordered.

The next section of program to be executed is Procedure CLOCK which is processed once in each "revolution" of the program loop. The primary function of CLOCK is to update the software clock at one minute intervals, and then, according to the time of day, to change the status of certain flags so that various time-dependent functions are executed at the correct time. These are as follows:

(1) 07h45:

FLAG3 is set to 1, so that when Procedure PRINT3 is encountered that section of program is executed to provide a listing of the equalization tank response for the previous 24-hour cycle.

(2) 12h00:

FLAG13 is set to 1, and Procedure TODISK is executed when next encountered in the program loop. This involves writing the updated version of all the historical inflow rate data stored in the microprocessor memory to files on the mini-floppy disc. In this way, if there is, say, a power failure, the control strategy can be restarted with historical data which is never more than 24 hours old.

(3) 19h00:

During normal work hours the operator is required to check and, if necessary, change the status of the three Day Type Switches on the interface unit; these switches indicate whether "Today", "Tomorrow", and the "Next day" are either weekdays or weekend days (or public holidays). At 19h00 the status of these switches is monitored by CLOCK so that from midnight the historical influent flow rate patterns used by the equalization algorithm can be set up appropriately.

(4) 10 minute intervals:

At 0, 10, 20, , 50 minutes past the hour FLAG14 is set to 1; this allows Procedure SERVCLOCK to be executed at 10 minute intervals. SERVCLOCK provides several functions which may differ depending on whether or not the time corresponds to the start of a new control interval.

- At the start of a control interval SERVCLOCK will (1) adjust certain program counters for use by the equalization algorithm according to the time of day, and (2) compute the distribution of the optimal total tank outflow rate for the ensuing control interval between the three tank outlets. If the outflow rates are to be set by the microprocessor for the first time then the appropriate values are written to the three DAC's for transmission to the outflow rate controller setpoints.
- Each time SERVCLOCK is executed FLAG12 is set to 1; this causes Procedure EMERGE to be processed every 10 minutes - EMERGE has two principal functions. The first is to perform a check on the reasonableness of the signals from the monitoring instruments; if the measurements do not fall within certain ranges or if the actual outflow rates are very different from the requested values, then an appropriate error message is printed and the system is automatically taken off line, thereby reverting to the manually-specified setpoints. The second function of Procedure EMERGE is to make small adjustments to the three flow controller setpoints on the basis of the differences between the actual and requested outflow rates.

4.1.4 Distribution of Flow Between the Tank Outlets

The Goudkoppies plant is designed to handle a daily average inflow of $150 \text{ M}\ell.\text{d}^{-1}$; it is intended that each of the three biological process modules should receive an almost constant flow of $50 \text{ M}\ell.\text{d}^{-1}$. However, at present the plant is underloaded, with a total inflow

in the region of 90 to 110 Ml.d^{-1} during the week, and 60 to 80 Ml.d^{-1} over the weekend and on public holidays. To date the practice in operating the plant has been to maintain the flow to two of the biological process modules as close to the design flow rate of 50 Ml.d^{-1} as possible, and to divert a lesser amount of flow to the third module. When the setpoints for the three outflow rate controllers were specified manually difficulties were encountered in applying this method of flow distribution; these problems again arise from the inability of the plant operators to estimate daily inflow rates with sufficient accuracy in advance. However, many of the difficulties of applying this approach are by-passed when the outflow rates are controlled from the microprocessor.* In the mainline program distribution of the total optimum tank outflow rate occurs as follows:

On starting up the control strategy the microprocessor prompts for various bits of information which is input from the keyboard. One of these is whether or not one of the three modules is to receive a stream of a specific flow rate, and if so, what this flow rate should be. If one of the flows is specified in this manner then, at the beginning of each control interval the remaining portion of the total outflow is distributed equally between the other two modules.

This approach may appear to encompass some of the problems of manual operation in that the specified flow rate setting for one of the modules is again related to an estimate of daily inflow rate. In practice, however, the method appears to work very successfully; part of the reason for this success seems to be that, because the outflow rate data for each outlet is printed each day, the plant manager is able to optimize, to a degree, the flow rate of the stream sent to the third module. An additional benefit of this approach to flow distribution is that it affords a means for reducing the effect (on the two modules receiving close to the design flow) of the decreased inflow rate over weekends:

*The computational facility of the microprocessor would allow the development of a more complex method for distributing the flow in an optimal manner. However, on the request of Johannesburg Municipality, a method for flow distribution similar to the original was incorporated in the control strategy.

During the week the flow to Module 3 is generally set at approximately $15 \text{ M}\ell.\text{d}^{-1}$ i.e. each of the other modules receives an inflow of approximately 40 to 45 $\text{M}\ell.\text{d}^{-1}$. Over the weekend when the total inflow to the plant drops by about $20 \text{ M}\ell.\text{d}^{-1}$, the flow rate to Module 3 can be decreased to between 5 and 10 $\text{M}\ell.\text{d}^{-1}$; this action, although detrimental to Module 3, results in only a small decrease in flow over weekends to Modules 1 and 2 which are treating the major portion of the influent flow.

The facility to change the flow rate setting for the module receiving a specified flow (usually Module 3) is provided by Procedure MANSET. A request to check and/or change the flow rate setting is entered from the keyboard; the interrupt facility causes FLAG9 to be set to 1 - on execution of MANSET the microprocessor supplies the outflow rate setting and prompts for a change to the setting.

4.2 Machine Code Programs

Certain functions necessary for implementation of the control strategy are performed through executing one of a number of machine code programs which are resident in the microprocessor memory together with the mainline Pascal program. The various machine code programs are located sequentially in a section of memory which is not used by either the microprocessor operating system or the Pascal program. A complete listing of the machine code programs is provided in Appendix E; in this Section only the function of the different programs is discussed.

The programs can be divided into two categories on the basis of the manner in which they are accessed for execution, as follows:

- Programs that are executed through interrupts typed in from the keyboard, and which result in different sections of the mainline Pascal program being processed. Typically this involves processing of a request for printed output which is not provided by the mainline program on a regular basis.
- Programs that are executed on the basis of instructions

from within the Pascal program. An example of this would be transferring information to the digital-to-analog converters (DAC's) when an adjustment to an outflow rate is required; the required outflow rate settings are calculated within the Pascal program - transferring this information to the output ports of the DAC requires execution of a machine code program.

4.2.1 Program for Processing Keyboard Interrupts

All the different components of the mainline program are located in separate procedures (or subroutines) which are tied in to a continuous program loop. Whether or not a particular procedure is processed depends on the status of a software flag associated with each of the procedures; a flag value of 1 leads to processing of the procedure, while a value of 0 causes the procedure to be disregarded during execution. Certain of the software flags are controlled from within the mainline program; these flags are used to ensure the appropriate implementation of the control strategy through scheduling execution of the different procedures at the correct times. Other flags are used to control the execution of procedures which do not form an integral part of the control strategy, but which are included so that information regarding the behaviour of the system (both the strategy and the equalization tank) can be provided on request. Manipulation of these flags, to enable processing of procedures not accessed during normal operation, is achieved by using the interrupt facility of the microprocessor; this aspect is now discussed.

On starting up the control strategy the ACIA, which controls the passage of information between the keyboard and the microprocessor, is manipulated to allow interruption of normal processing.* Thereafter, if any character on the keyboard is touched execution of the Pascal program is momentarily suspended while a section of machine code causes the character to be printed. To prevent inappropriate use of the interrupt facility, which may upset the normal operation, it is necessary to type in a keyword. In this case, if the word HELLO is typed on the keyboard, followed by a

* Usually while a program is being executed the keyboard will be "dead" i.e. any character typed in from the keyboard is disregarded by the microprocessor.

carriage return, the machine code responds with a message prompting for an "option number" as follows:

```
HELLO
```

```
HELLO! - Correct entry!
```

```
SPECIFY OPTION NUMBER (C.R.)
```

```
IF UNSURE OF OPT. NO. ENTER P
```

There are nine different one-character options that can be entered i.e. P, 1, 2, 4, 5, 6, 7, 8 or 9. On entering one of these, execution of the Pascal program is interrupted, and a section of machine code is processed to store a 1 in a specific memory location (for a particular flag). The Pascal program regularly scans these memory locations, setting the values of the software flags equal to the values stored in the appropriate location (by using the PEEK command). In this way certain of the procedures in the mainline program can be opened for processing from the keyboard. A listing of the possible option numbers and the corresponding output can be obtained by typing in HELLO followed by a P :

LIST OF INTERRUPT OPTIONS

OPT. NO.	ACTION
1	PRINT INPUT DATA
2	PRINT HISTORICAL DATA
4	PRINT EXPECTED RESULTS FOR NEXT 24 HOURS
5	PRINT LEVEL SENSOR READING
6	PRINT CURRENT ERROR EXPRESSION VALUES
7	COMPARE ACTUAL AND REQUESTED OUTFLOWS
8	CHECK AND/OR CHANGE TIME OF DAY
9	CHECK AND/OR CHANGE SPECIFIED FLOW

Of these eight options designated by the characters listed above, six provide printed output reflecting the behaviour of the control strategy and the equalization tank. The remaining two cause either

FLAG8 (for Procedure TIMSET) or FLAG9 (for Procedure MANSET) to be set to 1; these allow, respectively, the software clock to be checked (and changed if necessary) and the specified flow rate setting for a module receiving a specified flow to be altered via the keyboard.

4.2.2 Programs Executed from Mainline Program

The machine code programs discussed above were those executed as a result of keyboard commands to allow different sections of the mainline program to be processed. The remainder of the machine code program consists of a series of sub-programs which are processed at appropriate times through specific commands within the mainline program. Processing is diverted from the Pascal program through the USER command. This command in the Pascal package allows processing to be diverted from the mainline program to one of the machine code programs; once the machine code program has been executed control reverts to the mainline program. When the USER command is encountered in the Pascal program, processing is directed to a jump table (or directory) in the machine code program; then, depending on the value passed in the calling list of the USER command, one of the machine code subprograms is executed.

The individual sections of the machine code program, with a description of their functions, are:

MCPULS: Operation of the control strategy involves moving around a program loop continually; each "revolution" of the loop requires only a few seconds. If the operation of program is upset for some reason, and the looping stops, then it is necessary that the control strategy be taken off-line. To achieve this, MCPULS is executed once during each loop; the function of MCPULS is to re-set an incremental counter in the interface unit. If normal program operation is upset, however, then MCPULS is not executed and the counter is not re-set; after about 20 seconds the microprocessor is taken off-line and control of the tank outflow rates reverts to the manually specified setpoints on the flow controllers. Initialization of the

control procedure from start-up (before the program loop is entered) requires input of information from the keyboard over a period of about 2 minutes; in this case the trip-out facility must be overridden by a switch on the interface unit (Trip/Override Switch), to prevent unintentional tripping.

MCALRM: One of the functions of the mainline program is to check the reasonableness of the tank hold-up reading and the three outflow rate measurements; this check is provided by Procedure EMERGE at regular 10 minute intervals. If these values do not lie within certain specified limits then EMERGE outputs an error message identifying which signal is faulty before reverting to the manually specified flow controller setpoints. At this point MCALRM is executed, causing a bleeper in the interface unit to sound; this continues until the alarm cancel button on the interface unit is depressed.

MCPIA: The functions of the Parallel Interface Adaptor (PIA) have been described in Section 3.1.1. To provide these functions it is necessary to initialize the PIA; this involves setting up one of the two 8 bit parallel ports as inputs and the other as outputs. At the start of control strategy operation execution of the mainline program is diverted to the machine code program MCPIA (via the USER command); MCPIA sets up the A side of the PIA as outputs and the B side as inputs.

MCCLOCK: Implementation of the control strategy requires monitoring of real time. On initiating operation, the mainline Pascal program prompts for the time of day (in hours and minutes); this information is supplied by the plant operator via the keyboard. Thereafter, once during each "revolution" of the program loop, the status of a 2 bit binary counter is checked to ascertain whether or not the software time requires updating. Monitoring the status of the counter is carried out by diverting execution from the Pascal program to the machine code program MCCLOCK which

checks for 0's or 1's in bits 0 and 1 of the PIA input port. The decimal value of the 2 bit binary counter is incremented at one minute intervals from 0 to 1 to 2 to 3 to 0 and so on; therefore, providing the status is checked at least once every four minutes, the software clock can be suitably updated - usually the counter is monitored at about 5 second intervals so that the software clock is accurate to the minute.

MCADC: During operation of the control strategy the four measurement signals from the plant - three outflow rates and the tank hold-up - are regularly monitored. This requires reading the digital output on the appropriate output ports of the ADC, and is achieved by calling the machine code program MCADC from the mainline program. The inputs to the ADC are voltage signals in the range 0,5 to 3,5V; when the program MCADC is executed the equivalent digital value in the range 0 to 255 is placed in the four memory locations \$7810-\$7813 for access from the mainline Pascal program.

MCDAC: When it is necessary to supply new setpoint signals for the three tank outflow rate controllers the appropriate digital values in the range 0 to 255 are placed in the memory locations \$7821, \$7822 and \$7823 by the Pascal program (using the POKE command). Execution is then diverted to the machine code program MCDAC which sequentially places the values in those memory locations on the 8 bit output port of the PIA and transfers the data, via a latch, to the appropriate DAC which in turn converts the digital signal to an analog voltage output in the range 0 to 5V. An additional function of MCDAC is to set the status of the "local/auto" switches according to whether or not the tank outflow rate is to be set from the microprocessor.

MCDAY: Three switches of the interface panel are set by the plant operators to indicate whether "today", "tomorrow" and the "next" day are weekdays or weekend days. Once a day (at 19h00) the machine code program MCDAY is called from the mainline program to evaluate the status of the three switches

according to whether a 0 or a 1 is located at bits 2, 3 and 4 of the PIA 8 bit input port. Depending on these values either a 1 (for a weekday) or a 2 (for a weekend day) is stored in the memory locations \$7831, \$7832 and \$7833. The Pascal program can then access the values in these locations as information for setting up the expected influent flow rate patterns, and automatically make the required changes at midnight.

5. INSTALLATION OF EQUIPMENT AT GOUDKOPPIES WWTP

The microprocessor and ancillary equipment for implementation of the control strategy at the Goudkoppies WWTP, Johannesburg, was installed during February, 1981. The initial development of the system, which was carried out in Cape Town, involved three phases:

- Selection and purchase of a suitable microprocessor (with VDU, mini-floppy disc drive and printer), as well as the software required for the development of the control strategy computer programs.
- Design of the electronic circuitry located in the interface unit, and the assembly of this unit.
- Development of the computer programs for the real-time implementation of the control strategy.

Once these aspects of the development had been completed the system was bench-tested extensively over a two week period. The objective here was to test the operation of both the hardware and software components of the system. The major portion of this exercise involved monitoring the response of the control strategy under simulated real-time conditions by linking the system to a second microprocessor which was programmed to simulate the behaviour of the equalization tank. This method allowed the system to be tested over a wide range of situations (both usual and unusual) in a relatively short time, and was successful in identifying several features that required slight modifications.

When the equipment was accepted as being complete it was transferred to the plant in Johannesburg. Before the system could be linked

up to the equalization tank and brought on line, several tasks had to be completed:

Installation of float unit: The float unit (see Section 3.4) used for measuring the tank hold-up was manufactured by a Johannesburg firm. The unit was fixed to the inner wall of the equalization tank as per Fig 7.9.

Modifications to existing flow controllers: The circuitry for the existing flow controllers is located in three water-proof panels located on the outer wall of the equalization tank adjacent to the three tank outlets. It was necessary to make small adjustments to this circuitry so as to allow the set-points for the controllers to be specified from the microprocessor. These modifications were made by the firm which had originally installed the controllers and which is responsible for maintenance of the units.

Cable from plant to microprocessor: The most convenient location for the microprocessor and the interface unit is in a small laboratory building which stands between Modules 1 and 2 of the activated sludge plant. The main advantages of housing the unit in this building are that:

- The building is relatively dust free. At the Goudkoppies plant surface aerators are used in the aerobic zones of the biological process; on windy days fine droplets of entrained mixed liquor from these zones tend to permeate most of the other buildings, and, on drying, leave a dusty deposit on all surfaces.
- The annual temperature range in the building is relatively small, even though the outside temperature will usually vary between -4°C and 36°C . Therefore, the microprocessor will always operate well within the specified operating temperature limits.
- This location allows convenient access for the plant operators during both day and night shifts.

The one disadvantage of locating the microprocessor and interface unit in this particular building is the relatively long lines required for transmitting signals between the microprocessor and the plant. The line-of-sight distance between the two is approximately 70 metres, and a cable length of 125 metres was required to carry the various lines. As the cable passes close to a number of large electric motors (for the aerators) it would have been preferable to use well-screened industrial cable so as to avoid the possibility of picking up spurious signals on the lines. However, in terms of the limited budget and the short term nature of the project (from the research point of view) it was decided that this alternative would have been too costly; instead, inexpensive 20-core telephone cable was used. To reduce the effects due to the proximity of the electric motors, where the cable is routed close to the motors it is passed through metal conduit earthed at a number of points. This appears to be satisfactory for, up to the present, no interference effects have been noted.

Once the plant modifications discussed above had been completed the microprocessor was linked up to the plant. Before setting the control strategy in operation it was necessary to check the calibration of those sections of the interface unit used for conditioning the signals passing between the microprocessor and the measuring and control instruments on the plant. For this purpose a short Pascal computer program was written to execute the two machine code programs MCADC and MCDAC which, respectively, monitor the incoming signals and specify setpoints for the flow controllers. Having completed this procedure, the system was brought into operation.

CHAPTER EIGHT .

PERFORMANCE OF THE CONTROL STRATEGY AT FULL-SCALE

1. INTRODUCTION

In Chapter 7 a detailed description of the technical aspects involved in the implementation of the equalization control strategy at the Goudkoppies WWTP was presented. Much of that description provided information particular to implementation at Goudkoppies; for example, the fact that there are three tank outlets added complexity to both the hardware and software requirements necessary for the implementation — in many applications it is likely that there will be only one tank outlet. In addition, much of the information in Chapter 7 on the hardware and software is unique to the packages employed in this particular instance. Clearly other systems could have been used; in that case the content of Chapter 7 would have been different. For these reasons, development of the hardware and software systems for implementation of the control strategy at the Goudkoppies plant was presented as a separate Chapter. However, despite these specificities, much of the information in Chapter 7 should provide a useful base for anyone presented with the problem of developing a control system at any location.

Although the technique of implementation necessarily contains elements specific to the installation, the equalization algorithm operation is free of this. In this Chapter, therefore, we return to the general — the performance of the control strategy at full-scale.

2. SELECTION OF STRATEGY CONSTANTS AND PARAMETERS

The microprocessor-based control strategy was brought on line for the first time at approximately 07h40 on a Saturday morning. Prior to start-up it was necessary to specify values for a number of parameters or constants utilized by the equalization algorithm: namely.

- (1) Upper and lower allowable tank hold-up limits.
- (2) Error expression weighting factors.
- (3) Magnitude of the incremental change when an adjustment

is made to the outflow rate profile used by the algorithm.

- (4) Historical influent flow rate patterns for both a week-day and a weekend day.
- (5) The control interval length.

2.1 Hold-up Limits

The upper and lower allowable tank hold-up limits were initially selected as 95 and 20 percent, respectively, of the maximum possible hold-up. For the upper limit, a value of 95 percent is perhaps overly conservative because overflow from the tank in any case will be passed to the downstream modules. However, it was decided rather to be conservative in this selection, to allow for any initial instability in the operation of the control strategy. Appropriate selection of the *lower* allowable hold-up limit is important; this value must be such that each day the hold-up drops to below the level of the dwarf walls (700 mm; 24% hold-up) on the floor of the tank so as to scour out any particulate matter which may settle on the base of the unmixed tank. For the Goudkoppies application there is also a lower limit to the value that can be chosen because, if the tank level drops to below about 500 mm (17% hold-up), the head is insufficient to maintain the required outflow rate from the tank. For these reasons an intermediate value for the lower hold-up limit of 20 percent was selected; this value should result in the tank level dropping to about 600 mm during each cycle.

2.2 Error Expression Weighting Factors

The contents of the Goudkoppies equalization tank are not mixed. The implications of this aspect have been discussed in Section 2, Chapter 7; the consequence, in terms of application of the control strategy was that initially only *flow* equalization could be set as a verifiable objective for the operation - not *flow and load* equalization.* This meant that a value for the equalization error weighting factor, $\alpha = 1$, had to be selected for this application. The value of α has no

* It was decided first to determine the influence of flow equalization on load equalization in order to determine whether or not it is necessary to incorporate, in the control strategy, an empirical model for the settlement and scouring of solids so that the load equalization, *per se*, can be included as an objective.

bearing on the selection of the values for the penalty error weighting factors, β and ω ; these are selected merely on the basis of ensuring appropriate behaviour of the penalty errors - from past experience with applications of the algorithm and simulations of the control strategy operation values of $\beta = 2 \times 10^{-6}$ (for the hold-up limit penalty error) and $\omega = 25$ (for the penalty error for rate of change of outflow rate) were selected.

2.3 Incremental Flow Rate Adjustment

The algorithm simulates the expected response of the equalization tank for an ensuing 24-hour cycle to determine the optimum expected outflow rate profile under the expected 24-hour input of flow. The *actual* outflow rate for the control interval under consideration is set according to the value for the corresponding section (i.e. the first section) of the expected optimum profile for the ensuing 24-hour cycle. By repeating the simulations at regular intervals operation of the equalization facility is continuously optimized.

In a simulation of the expected tank response for any ensuing 24-hour cycle the inflow and outflow profiles are divided into a number of intervals and numbered with the interval under consideration being number one, and the remainder in sequence for the 24 hours following. The simulation intervals are chosen to correspond to the control intervals over the day, and then, starting with the first interval, the effect of an incremental change (either up or down) in outflow rate at each interval in the cycle is assessed (through the error expression value). Once the full cycle of changes has been attempted (and changes possibly accepted at certain intervals), the procedure is repeated from the first interval until, in a full cycle, no adjustment to the simulated outflow rate profile leads to a decrease in the magnitude of the error expression. For the simulation, selection of the magnitude of the incremental flow rate adjustment (called LIMIT in the computer program) requires a balance between a value which is neither too large nor too small:

- If LIMIT is too large the optimization procedure can become unstable, and the final outflow rate profile is not the optimum one. In addition, large changes in outflow

rate will be made at the start of control intervals nullifying, to a degree, the objective of flow equalization.

- If LIMIT is too small then, even though the resulting outflow rate profile may be very close to the optimum in this that the method will allow very small changes in outflow to be distributed over the full cycle, computation time required for application of the equalization algorithm becomes inordinately long.

In the real-time application another aspect imposes a lower limit on the magnitude of LIMIT - the minimum size of adjustments to outflow rate that can be made by the flow controllers on the outlets from the tank. At the Goudkoppies plant the size of these adjustments is approximately 10 l.s^{-1} on each of the three tank outlets. Under the selected operating procedure, the flow to Module 3 is held constant and changes in outflow rate are distributed evenly between the other two modules (see Section 4.1.4). Therefore, the magnitude of LIMIT which equals the minimum size of the total outflow rate adjustment from one control interval to another, is approximately 20 l.s^{-1} . In the computer program LIMIT is specified as a fraction of the mean outflow rate and initially was assigned a value of $\text{LIMIT} = 0,22$; as the mean flow rate is about 1200 l.s^{-1} , this corresponds to a minimum possible change in outflow rate of approximately 24 l.s^{-1} , which exceeds the minimum allowable value and, therefore, is acceptable.

2.4 Historical Influent Flow Rate Profiles

The equalization algorithm requires historical inflow rate data for two different 24-hour input patterns - one for the weekday pattern and and for the weekend/public holiday pattern. The number of data values required for each pattern corresponds to the number of control intervals over the day. For example, if 30 minute control intervals are utilized, then each outflow rate profile consists of 48 values with each value reflecting the mean historical inflow rate expected over a particular interval. The initial historical profiles need not be particularly accurate because it is the function of the control strategy to continuously update the profiles. However, the period from start-up until operation of the strategy is stable, will be reduced if

reasonably accurate initial profiles are used. In this case the initial historical data for the two profiles was obtained from a rough analysis of inflow rate data over the weeks prior to start-up of the strategy.

2.5 Control Interval Length

Guidelines for the selection of control interval length on the basis of tank size have been presented in Section 4, Chapter 6; these indicated that control intervals of 30 minutes would be appropriate for the application at Goudkoppies where the equalization tank has a mean retention time of approximately 5 hours (based on the present mean inflow rate). Further to this, considerations regarding computation time in the real-time application of the control strategy also indicated that a control interval length of 30 minutes would be suitable (see Section 4.1.1, Chapter 7). For both these reasons 30 minute control intervals were accepted; that is, the control strategy will possibly cause a change in outflow rate at half-hourly intervals provided that emergency control action is not required during an interval.

3. INITIAL PERFORMANCE OF THE CONTROL STRATEGY

The control strategy was set in operation for the first time in 07h40 on a Saturday morning; with control interval lengths of 30 minutes this meant that the outflow rate from the equalization tank was specified by the microprocessor from 08h00 onwards. Figure 8.1 shows details of the behaviour of the control strategy over the first six days of continuous operation i.e from Saturday morning until midnight on the following Thursday. These results are presented in three sections, as follows:

- The top section shows (1) the actual inflow rate to the equalization tank over the period, and (2) the historical influent flow rate profile stored in the microprocessor memory and used by the equalization algorithm. In the case of the *actual* inflow rate, a smooth curve was drawn through data points calculated for the mean inflow rates over half-hourly intervals. Consequently "noise" effects indicated by rapid, random fluctuations about the trend pattern were excluded. This was done to facilitate interpretation of the

results. Similarly, a smooth curve was drawn for the *historical* pattern even though discrete values of the mean inflow rate over 30 minute intervals are stored in the microprocessor memory.

- The centre section shows the *total* tank outflow rate over the period i.e. the sum of the three tank outflow rates.^{*} This data plots as a stepped function with the step lengths reflecting the frequency at which the outflow rate was changed by the control strategy.
- The tank hold-up variation over the period is illustrated in the bottom section. The data is presented as a percentage of the total tank hold-up.

The outflow rate profile indicates a considerable attenuation of the influent flow rate variations; however, the profile does exhibit some troughs and peaks that seem contradictory to results indicated by the simulations of controlled equalization response in earlier Chapters. In addition, over the weekdays the full tank capacity available was not utilized. The apparent non-optimal response was not due to the strategy itself. The response of the control strategy from interval to interval over this initial period of operation can be explained exactly in terms of differences between the actual and historical inflow rate patterns and the tank hold-up situation, indicating that the strategy was operating in an optimal manner in terms of the criteria laid down in the error expression. The non-optimal behaviour over the initial period of operation can be ascribed to two features: (1) the starting conditions, and (2) inaccuracies in the initial historical influent flow rate patterns.

- (1) Starting conditions: Up to 08h00 the outflow rate from the equalization tank was controlled by manual operation i.e. non-optimally; setpoints for the three outflow controllers had

* The function of the equalization algorithm is to calculate the optimum *total* outflow rate from the tank; this outflow rate is divided between the three tank outlets by the control strategy in accordance with the procedure outlined in Section 4.1.4, Chapter 7. Over the period considered here Module 3 received a constant flow rate of 170 l.s^{-1} , while the remainder of the total outflow was evenly distributed between Modules 1 and 2.

been specified by the plant operators. As was to be expected, the tank hold-up on starting up the control strategy operation (55%) was substantially different from the value (of about 25%) which would have been encountered had the tank been under the control of the microprocessor over the preceding cycles. Therefore, over the first day of microprocessor operation, the action of the strategy was to "force" the tank towards the optimal situation in an effort to stabilize operation.

- (2) Initial historical inflow rate patterns: Over the first two days the actual inflow rate pattern was very different from the historical pattern - in general the historical patterns under-predicted the actual inflow rate. Differences between the actual and the historical inflow rate patterns for the period from Monday to Thursday were not as marked as the differences over Saturday and Sunday but the actual inflow pattern still differed from the initial weekday historical pattern over three periods in the daily cycle. Differences are particularly evident in the patterns for the Tuesday, Wednesday and Thursday:
- Over the period of minimum inflow between 02h00 and 07h00 the actual inflow rate dropped *below* the historical values.
 - Between 06h00 and 10h00 the inflow rate tended to rise more rapidly than reflected in the historical pattern.
 - Over the period of maximum inflow the historical data over-predicted both (1) the peak flow rate, and (2) the period for which the peak flow rate is sustained.

Over the weekdays, as noted above, the principal differences in flow rate occurred over the periods of maximum (peak) and minimum daily inflow rates; in both instances the expected (historical) exceeded the actual inflow rates. As a consequence, in approaching (and during) the peak flow periods, the strategy anticipated a large inflow and appropriately made provision for more storage volume to be available over the peak flow period by increasing the outflow rate. When the high inflow does not materialize, the result is that the tank hold-up only attains a maximum of approximately 85 percent of the total even though the

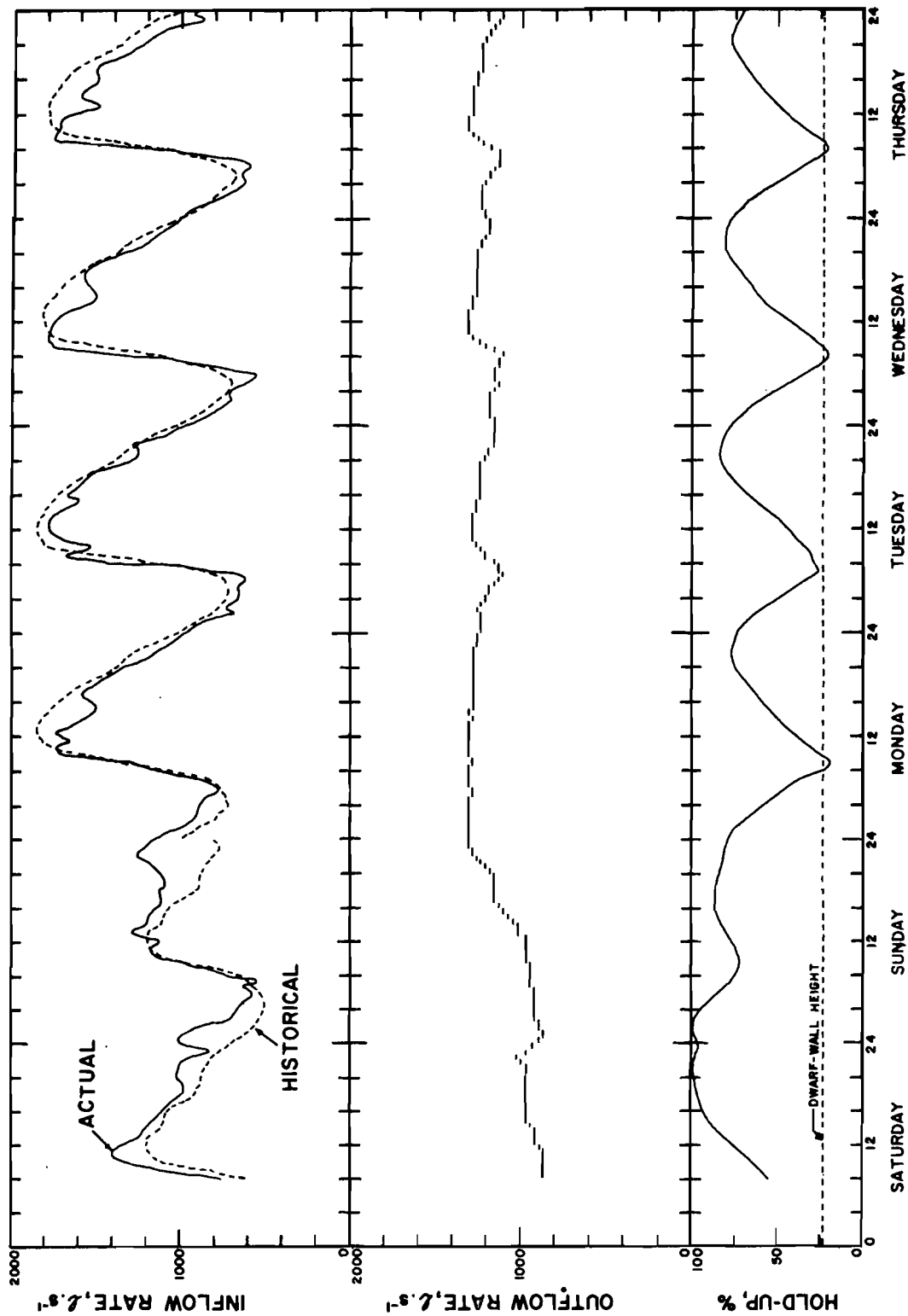


Fig 8.1 Response behaviour of the Goudkoppies equalization tank over the initial period under continuous control strategy operation.

upper allowable hold-up limit is specified as 95 percent. During the periods of low inflow the strategy again expects a larger inflow than that which actually occurs; in consequence, the strategy sets the outflow rate at a higher level than would have been the case if the historical and actual inflow patterns were the same. When the actual inflow rate, in fact, is over-estimated the tank empties faster than anticipated; the lower hold-up limit penalty error is activated and the flow rate is reduced fairly drastically, to cause the sharp trough during this period.

The result of these differences was to increase the period required for operation to stabilize; the period for stabilization was further affected by the occurrence of a rainstorm in the collection area on the Sunday afternoon which resulted in a substantial increase of the actual inflow rate over the latter part of Sunday through ingress of stormwater in the sewer system.

The effects of the incorrect starting conditions and the inaccurate initial historical inflow rate data were different in so far as their influence on the period required for operation to stabilize was concerned. The effect of a non-optimal hold-up when the control strategy was brought on-line is inconsequential; after 24 hours of operation the effect is virtually eliminated. In contrast, the effects of marked differences between the historically-expected and the actual inflow patterns persisted for a longer period, principally because the updating procedure for the historical data is relatively slow, so that the historical inflow profiles approach the actual profiles only after a number of daily cycles have been completed.*

*Updating the historical inflow rate data is demonstrated in the results shown in Fig 8.1:

On the Monday the historical peak inflow rate value was 1850 l.s^{-1} ; however, on that day and the subsequent days, the actual inflow rate does not reach this level. Careful scrutiny of the results shows that, by Thursday, the peak historical value has been progressively reduced to 1800 l.s^{-1} .

It might appear that the historical data is updated at an overly slow rate: (each day the new historical mean influent flow rate over an interval is taken as the sum of 95 percent of the current historical value and 5 percent of the actual mean inflow rate over that interval). However, the reasons for this small weighting of the actual inflow rate are cogent and have been discussed in Section 3.1.1, Chapter 5; therefore, the slow rate of convergence is an inbuilt characteristic of the strategy and the behaviour indicates no abnormality.

4. STABILIZED OPERATION OF CONTROL STRATEGY

In time, as the historical influent flow rate data stored in the micro-processor memory was updated to reflect the actual inflow rate profiles more closely, so the response of the equalization tank stabilized, and the quality of the flow equalization improved. In Fig 8.2 the results obtained over a week's operation under stabilized conditions is shown. (For purposes of comparison the data is plotted in the same format as in Fig 8.1 for the first week's operation). The performance closely follows the results predicted from the simulations in Chapter 6 indicating that, once the historical and actual influent profiles are in close agreement, a high level of equalization efficiency can be expected. It is not necessary to interpret the reasons for each individual change in outflow rate over the week to confirm that the control strategy is behaving in the expected manner; this aspect has been discussed for the results in Fig 8.1. However, features worth noting from the results of Fig 8.2 are:

- Over the midweek period (i.e. Tuesday, Wednesday and the previous Thursday) the tank outflow rate is very near constant; the flow rate varies within limits of $\pm 3,5$ percent of the mean value.
- In the transition from a week to a weekend, and *vice versa*, when there is a marked change in inflow rate, the required change in outflow rate is spread over a full 24 hour cycle; commencing early Friday and early Sunday there is a gradual trend to decrease and increase the outflow rate, respectively.
- On the Saturday the tank hold-up is only reduced to a minimum of 34 percent of the total although the lower allowable limit is 20 percent. The action of the strategy is to retain flow on the Saturday for use during the latter part of the period of decreased flow i.e. over the Sunday. On the Sunday the tank level is allowed to drop to its lower limit so as to maintain a reasonable outflow rate.

The study of Fig 8.2 can only serve to reinforce the conclusion that there can be little doubt about the effectiveness of the control strategy under real-time conditions to smooth and equalize the flow pattern in a very efficient manner. The advantages of utilizing the

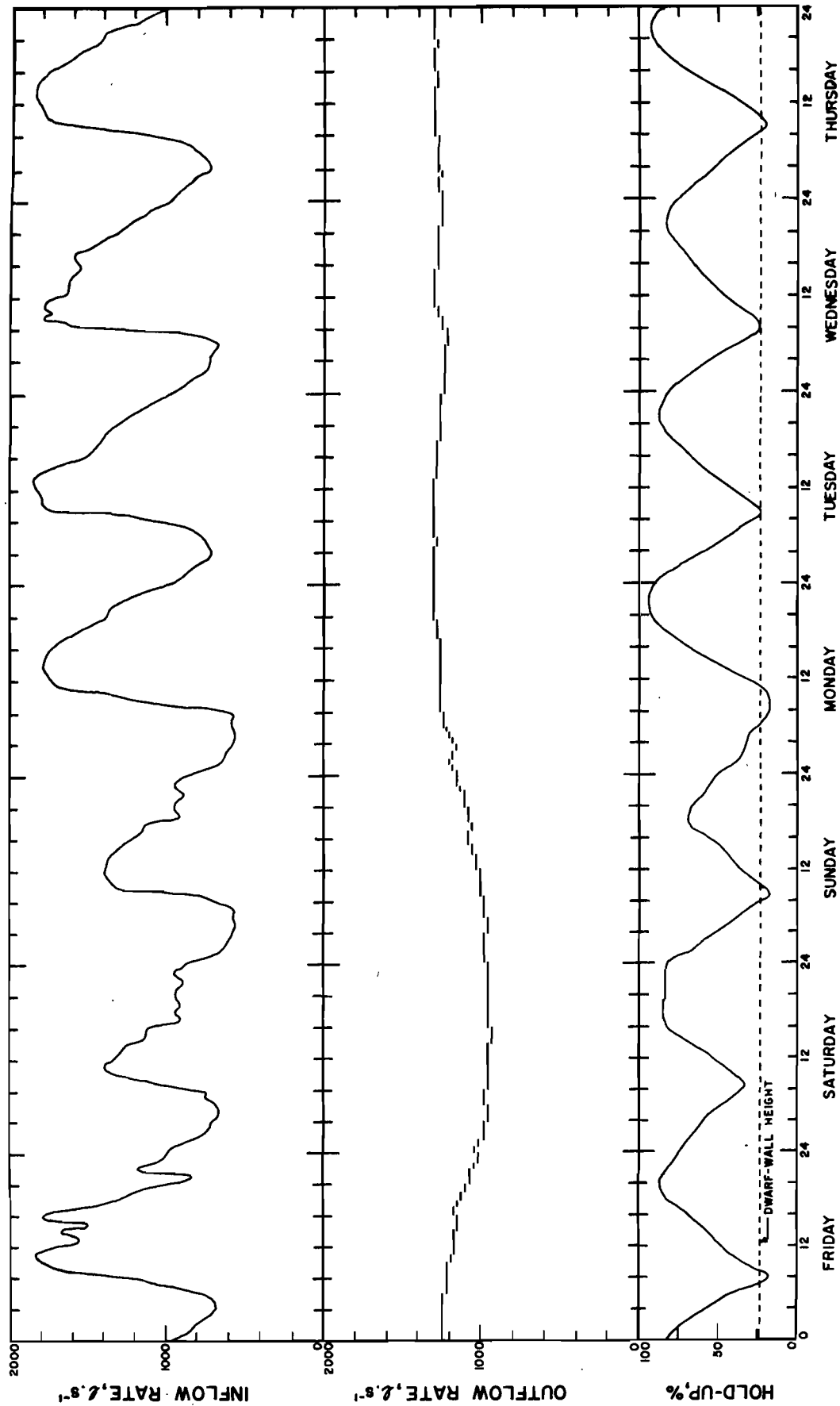


Fig 8.2 Response behaviour of the Goudkoppies equalization tank over a period of one week under stabilized control strategy operation.

control strategy are further exemplified by comparing the results of Fig 8.2 with those obtained when the flows were controlled by manually setting the outflow controllers: The results presented in Fig 2.14 (p 2.26, Chapter 2) illustrate the response of the equalization facility over a period of one week under the manual mode of operation; these results, when compared with those obtained under the control strategy, clearly illustrate how the strategy leads to far superior utilization of the equalization facility. Several features are worth mentioning in this regard:

- Comparison of the results in Fig 2.14 and Fig 8.1 show that even during the first few days of operation under micro-processor control (before the operation had properly stabilized) the behaviour was far superior to that obtained under manual control.
- During operation under the control strategy the equalization tank will seldom, if ever, overflow (this problem might occur only on the first day after start-up depending on the tank hold-up situation when the microprocessor is brought on-line). In contrast, under manual operation overflow was an almost daily occurrence.
- Under control strategy operation the level to which the tank drops during each daily cycle can be specified and controlled quite accurately. This is particularly important in the Goudkoppies operation to ensure that no accumulation of solids on the base of the tank will take place (for more stable operation of the downstream biological process). If, however, it should be desired to retain solids in the equalization tank for some reason, this can be attained by specifying a higher value for the lower allowable tank hold-up limit.
- Under the control strategy a gradual transition from weekday to weekend, and *vice versa*, is attained. Although the weekend mean daily inflow rate at Goudkoppies is only about 75 percent of the weekday value, no sudden changes in outflow rate are reflected over the transition periods; the effect is spread over a full 24-hour cycle.

- A benefit of particular importance at Goudkoppies, which is likely to be repeated whenever the strategy is implemented, is that the strategy relieves the plant operators of a time-consuming and frustrating task. The inherent deficiencies of the manual flow control procedure (see Section 3.3, Chapter 7) made that the efficiency of equalization prior to installation of the strategy was very unsatisfactory despite the large amount of time devoted to the task of setting and re-setting the controller setpoints. Once the strategy was in operation the amount of operator attention was reduced to a few minutes each day.

5. EFFECT OF FLOW EQUALIZATION ON LOAD RATE VARIATIONS AT GOUDKOPPIES WWTP

The discussion so far has revolved around the performance of the control strategy with regard to equalization of *flow* rate, with no consideration for the load equalization aspect. This approach, mentioned previously, was taken because, on implementation at Goudkoppies, it was only possible to verify the flow equalization aspect of the control strategy for reason that the contents of the equalization tank are not mixed. It is of some interest, however, to assess the extent to which *load* equalization has been attained with an un-mixed tank operated with the specific objective of *flow* equalization only.

Figure 8.3 shows the measured response of both the tank effluent flow rate and COD load rate over a 24-hour period when the equalization tank was controlled by the strategy; the corresponding influent profiles are also shown in the Figure, together with the tank hold-up response. Although the load rate profiles are drawn as continuous curves, in actual fact the load was calculated from COD concentration measurements made at one hour intervals - the curves tend to accentuate deviations commonly exhibited by grab samples. Several important features are apparent from Fig 8.3:

- The effluent flow rate profile is almost constant; therefore, variations in the effluent load rate profile reflect, very closely, the effluent COD concentration variation.
- Comparison of the influent and effluent load rate profiles

show that there is, in fact, an appreciable degree of attenuation of the load variations (over this period at least). The peak load shows a reduction from 1,48 to 1,14 times the mean value, and the minimum load an increase from 0,12 to 0,60 times the mean.

- Up to the point where the tank hold-up and the influent load rate reach a minimum, the effluent load rate remains very

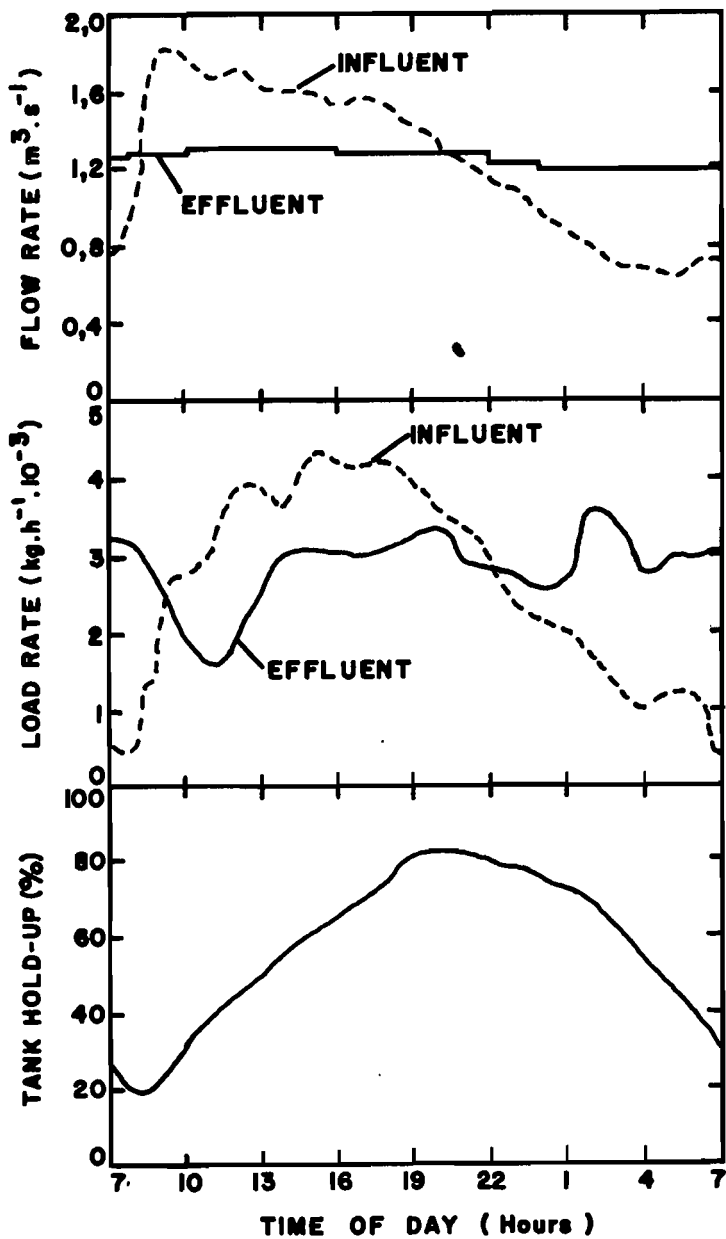


Fig 8.3 Effect of flow equalization on load rate for the un-mixed equalization tank at the Goudkoppies WWTP.

close to the mean value (behaviour not indicated in the simulations); there is a decrease in effluent load rate only after this time. This behaviour possibly is due to two effects: firstly, over the period when the hold-up is close to the minimum, particulate material which has settled on the base of the tank during the previous cycle is scoured from the tank, helping to maintain the effluent load rate close to the mean; secondly, the dimensions of the tank cause a partial plug flow effect across the tank from inlet to outlet, resulting in a lag in the decrease in effluent load rate with respect to the influent.

- For the 24-hour cycle considered here there is only a 1 percent mass loss in COD from the influent to the effluent. This contrasts sharply with the mass loss of approximately 20 percent across the tank when the tank was operated by human agency and retention of solids in the tank was an objective. Although this low value of 1 percent may be fortuitous, the controlled mode of operation whereby settled solids are flushed from the tank each day does appear to be successful. This is supported by the absence of gas bubbles rising to the surface - escaping gas previously indicated a high degree of anaerobic activity in the tank.

From the results presented above it would appear that even though (1) only flow equalization was specified as an objective, and (2) the contents of the tank were not mixed, the resultant degree of load equalization was not substantially different from the results obtained in simulations where both flow and load equalization are objectives. The results, therefore, indicate that benefits accruing from load equalization should be apparent at the Goudkoppies plant. For example, one should expect that control of aeration in the biological process under the equalized load pattern should demand less need for matching aeration rate to oxygen demand compared to the situation of no equalization. However, this, and other benefits, can be assessed fully only from monitoring plant behaviour over a period of several months. During the period the flow equalization behaviour was tested changes

were continuously being made in plant operating procedures in an effort to improve plant performance with respect to biological nitrogen and phosphorus removal. These changes made it difficult to evaluate the effect of the load equalization aspect on plant dissolved oxygen control, and other performance effects even though the results from monitoring equalization tank effluent COD load would indicate that such effects should be significant.

6. PROBLEMS ENCOUNTERED IN OPERATION AT GOUDKOPPIES

With regard to the operation of the control strategy itself, only very minor problems have been encountered in the application at Goudkoppies. Problems initially arose mainly as a result of incorrect calibration of the signals passing between the equalization tank and micro-processor resulting in false information being passed to or from the control strategy. If proper care is taken in setting up and calibrating the signals, then very likely it will be necessary only to check the calibration of these signals at intervals of a few months.* The frequency at which the calibration of the signals requires to be checked will be related to the manufacturers' specifications on the electronic components in the various bits of circuitry. For example, if relatively cheap pressure transducers are used in the measurement of tank outflow rates, generally these will require more regular checking than more expensive transducers, manufactured according to more stringent specifications.

The one major problem encountered in the operation at the Goudkoppies plant is damage to electronic equipment as a result of lightning strikes. The Goudkoppies plant is situated in the heart of the Witwatersrand area of South Africa; during summer months this region is renowned for the high incidence of violent electric storms.

Approximately one month after the microprocessor was brought on-line for the first time, certain of the electronic and electrical equipment on the plant was damaged during such an electric storm, including the equalization control equipment. Although the damage was only minor - requiring replacement of a few electronic components only, amounting to

* Checking the calibration is very simple. In the case, of say, the tank outflow rates, the microprocessor reading of the three outflow rates can be printed out and compared directly with the outflow rate readings displayed on the front of the panels housing the flow controller circuitry.

a few cents - it is evident that electric storms can put the equipment out of action.

The actual source of the damage as a result of lightning is difficult to ascertain. Three possibilities can be suggested:

- A direct strike either on, or close to the metal flow-controller panels, or, on the metal walkways close to these units.
- A current induced in the cable between the plant and the interface unit.
- A voltage surge transmitted on the mains supply.

Whatever the source of the problem, it would seem essential to protect the equipment in regions where occurrence of electric storms is a possibility. In the case of the Goudkoppies plant the possibility of damage from lightning was anticipated, and over-voltage protection is included on both the mains supply and all lines between the plant and the interface unit. Despite this protection, damage to the equipment did occur on the one occasion mentioned above.* Therefore, it would appear obligatory to obtain the services of an expert with a view, say, to opto-isolating all electronic circuitry so as to exclude the possibility of lightning damage completely.

* The Goudkoppies plant is particularly susceptible to damage by lightning. Damage has not been restricted to the equalization equipment - over the past two summers dissolved oxygen control equipment has been damaged severely on three occasions and an aerator motor completely destroyed.

CHAPTER NINE

SUMMARY AND CONCLUSIONS

The principal objective in this study was to develop a microprocessor-based "intelligent" control strategy operating on an equalization facility to provide near-optimal performance on a continuous basis i.e. specifically a control strategy which utilizes the available equalization hold-up volume in a manner that achieves the greatest possible degree of equalization of both influent flow and load rate.

1. MOTIVATION

Motivation for the development of an equalization control strategy came as the result of an enquiry into control of wastewater treatment plants, with particular emphasis on control within the South African context. From this enquiry it was evident that, in South Africa, in-plant control is not suited to nutrient removal processes, principally for the following reasons:

- The complex nature of these processes (which include anaerobic, anoxic and aerobic zones) necessitates a complex in-plant control strategy to ensure successful performance under dynamic loading conditions. A successful strategy for these conditions will have to rely heavily on the predictive power of a model describing both the activated sludge process response and the secondary clarifier behaviour - it is doubtful whether adequate models exist as yet.
- Some of the more important process parameters (oxygen utilization rate, nitrification) respond very sensitively to variations in flow and load inputs (a kinetic consequence of the long sludge ages of 15 to 25 days). This phenomenon makes for stringent, and perhaps complex, control requirements if successful process performance is to be achieved under variable load rate inputs. For example, both over- and under-aeration have an equally adverse effect on the process. Consequently, for adequate process control, accurate and

reliable monitoring equipment is essential. Stability of monitoring instrumentation at present is more the exception than the rule, so that back-up services are crucial; such back-up services do not exist country-wide in South Africa.

For optimum performance of these nutrient removal plants adequate control is so essential that attention was directed to equalization as an alternative to in-plant control. From a theoretical viewpoint, complete or near-complete equalization of both flow and load would reduce the required in-plant control to the simplest level, within the competence of the plant operator.* From a practical point of view, the following questions needed to be answered:

1. Is simultaneous equalization of flow and load possible ?
2. If so, will the instrumentation necessary for its implementation be simple and reliable enough that it will be within the competence of the operator to operate the system effectively, and, will the necessary back-up services (in the South African context) be adequate ?

To answer the first question required a thorough review of the work that had been done on equalization, and further theoretical work to develop the potential and define the limitations of the equalization approach. To answer the second question, consequential to an affirmative answer to the first, necessitated a wide-ranging enquiry into the needs for effective equalization, both for monitoring and implementation of a control strategy.

2. PROBLEM IDENTIFICATION

Theoretically, if the diurnal influent flow and load rate variations could be reduced to yield near-constant inputs of flow and load to a WWTP, then the need for control on the plant (e.g. aeration control)

* The selection of load, instead of concentration, as the parameter to define the pollution aspect needs some comment. The selection is justified from the kinetic behaviour of the activated sludge process. In terms of the process model developed by Dold, Ekama and Marais (1980), at long sludge ages variation in mass oxygen demand rate is controlled principally by the variation in load rate (i.e. concentration x flow rate), not by the variation in concentration alone.

would largely fall away. Yet despite such positive theoretical indications, in the literature many researchers concluded that there is little merit in equalization. However, an analysis of the basis for these conclusions indicated that these were mainly a result of a lack of understanding of the kinetic behaviour of the activated sludge process.

1. In many cases incorrect parameters were used to assess the effects of equalization. For example, evaluation of equalization performance was often based on effluent COD (or BOD) quality. However, because a large fraction of the influent COD is particulate material, the effluent COD is virtually insensitive to influent COD load rate variations as the particulate material is enmeshed and adsorbed by the sludge mass. Consequently, the use of the parameter as a criterion to assess the effectiveness of equalization is bound to show that little benefit is to be derived from equalization.
2. Much of the work on equalization was conducted on plants operated at very short sludge ages (< 3 days). From kinetic considerations, the response of the oxygen utilization rate in this situation is largely attenuated, even where variations in the influent loading conditions are substantial. Consequently, equalization could demonstrate very little benefit in terms of simplifying the problem of aeration control. This negative conclusion on equalization would have been highly unlikely had the evaluation included plants operated at long sludge ages. At long sludge ages both theoretical predictions and plant experience show that the process responds fairly sensitively to influent load fluctuations.
3. On settling tank behaviour, the literature often reports negatively on the effects of flow equalization. These negative reports were found to be associated with plants in which the settling tanks were considerably underloaded. However, for settling tanks loaded to full capacity equalization of the flow showed significant improvement of the effluent quality with regard to solids loss, by reducing the

day. It became clearly evident that, if the hold-up of the tank is to be used optimally, a predictive technique taking due cognizance of the variability of the influent pattern from day to day and between week and weekend needs to be incorporated in the control procedure, i.e. *in a control strategy*.

3. DEVELOPMENT OF A CONTROL STRATEGY

From the enquiry into the historical background of equalization it was evident that the operational procedure implicit in the cumulative flow hydrograph approach to design should be abandoned if equalization is to serve as an effective alternative to in-plant control, particularly if both flow and load equalization are set as the objective, and if the operational problems caused by variable daily inputs are to be overcome. Identification of deficiencies in this operational procedure, as traditionally practised, was helpful, however, in developing the structure of an equalization control strategy which can provide an adequate alternative to in-plant control. Two principal requirements of the control strategy structure were identified:

1. Whenever a control decision is to be taken it is necessary to consider the effect of that decision as a part of the full 24-hour cycle. Because of the interrelation of the parameters flow and load, no constant output value can be expected for either parameter over the daily cycle for optimal equalization of both - it was apparent that, if the flow rate remained constant at the mean value, the load rate could fluctuate quite appreciably, and *vice versa*. This observation necessarily accepts that, if optimal equalization of flow and load is to be achieved, a principal function of the strategy will be to vary the tank outflow rate (and effluent load rate) over the 24-hour cycle, but in the smallest degree consistent with the objective.*

* It would perhaps appear that the approach of allowing the outflow rate to vary over the 24-hour cycle would not be necessary if *flow* equalization is the sole objective. This is not always true: if the tank size is such that it is not possible to withdraw a constant outflow rate over the full cycle then it is again necessary to incorporate the possibility of varying outflow rate within the 24-hour cycle in an operational procedure. In this event it follows again that it is necessary to consider the full 24-hour cycle to obtain optimal utilization of the available hold-up volume.

2. Control decisions should be taken at short intervals (say, half-hourly). The daily cyclic inplant flow and load rate patterns are not repeated identically from day to day. To account for this variability it is necessary to re-assess control decisions at short intervals to obtain near-optimal operation on a continuous basis.

From identifying the requirements (1) and (2) above, it was possible to envisage the overall structure of a flow and load equalization control strategy without having to detail the actual method of operation (or the variables on which control action should be based). That is, control decisions should be made at short intervals and, in order to make a control decision, it is necessary to utilize some predictive technique for forecasting the expected influent patterns for the ensuing 24-hour cycle.

Once an outline of the control strategy structure had been proposed the first requirement in evolving the strategy was to develop a numerical procedure whereby, given a specified equalization tank size, the tank effluent flow and load rates would deviate the least from absolute constancy. In developing this numerical optimization procedure it was necessary (1) to attach relative weights to the importance of flow and load equalization, and (2) initially to assume that the daily cyclic influent patterns would be repeated identically from day to day.

1. Weighting factor for equalization. As the two interrelated parameters (flow and load) are independent *in so far as the calculation procedure for evaluating equalization is concerned* a weight had to be ascribed to the relative importance of equalization of each. For example, a weight of 1 for flow equalization (and corresponding 0 for load) would express the intention to equalize the flow rate without consideration of the load, and so on.
2. Selection of fixed daily cyclic influent patterns established a basis for the development of a numerical procedure to identify an optimal equalization condition. Acceptance of fixed daily input patterns implied that (1) all tank response

variables (hold-up, concentration, flow rate, etc.) necessarily must be the same at the beginning and end of each 24-hour cycle, and (2) mass balance principles must be obeyed. These conditions served a most useful function in that, for any proposed calculation procedure to obtain optimal equalization, if the conditions (1) and (2) are satisfied the procedure at least is stable and convergent.

To establish the numerical procedure required consideration of the situation as encountered in practice: The equalization tank hydraulic response is governed by a simple differential equation relating the change in tank hold-up, V , to the inflow and outflow rates, F_o and F_l , respectively, i.e.

$$dV/dt = F_o - F_l \quad (9.1)$$

In the situation under consideration the influent pattern, F_o , is fixed. In seeking an approach to the numerical procedure, to identify the optimal solution for a 24-hour cycle, it was first of all necessary to decide on whether one should either:

1. Determine the tank hold-up profile, V , under the cyclic inputs which results in optimal flow and load rate equalization, and from this determine the outflow rate profile, F_l , to be applied by the control strategy;

or

2. Determine the outflow rate profile, F_l , which results in optimal flow and load rate equalization, and from this determine the hold-up profile, V , associated with F_o and F_l .

In both cases a constraint on the tank hold-up is operative in that the tank must neither empty nor overflow during the cycle. After a thorough investigation, the second approach was found to be superior: By maintaining a "smooth" outflow rate profile, the tank acts as a buffer to rapid random variations exhibited by the input pattern in practice. In contrast, by imposing a "smooth" hold-up profile, sharp variations about the input trend pattern are transmitted to the downstream process, thereby nullifying, to a degree, the objective of equalization.

Development of a calculation procedure (using the outflow rate profile development approach) that will always advance to the optimal solution (i.e. development of an *equalization algorithm*) required formulation of an objective function to give an assessment, numerically, of the equalization: Accepting that the effluent flow and load rates will deviate from the mean over the daily cycle, it is necessary to quantify the combined deviation. This was accomplished by including two terms in the objective function (*error expression*) - one for the flow deviation, E_f , and one for the load deviation, E_{ld} . By selecting a weighting factor, α , the two components can be summed to provide a measure of the *equalization error*, E_e , which takes into account the relative importance ascribed to each equalization aspect:

$$E_e = \alpha E_f + (1-\alpha) E_{ld} \quad (9.2)$$

where $0 \leq \alpha \leq 1$

Formulation of the components E_f and E_{ld} was subjective. By trial it was found that successful results were obtained if each was calculated on the basis of the squares of the deviations from the respective mean values, integrated over the 24-hour cycle, i.e.

$$E_f = \int_0^{24} (F/\bar{F}-1)^2 dt \quad (9.3)$$

$$\text{and } E_{ld} = \int_0^{24} (L/\bar{L}-1)^2 dt \quad (9.4)$$

The procedure to determine the optimum outflow rate profile from an equalization tank of a specified size, under known 24-hour inputs of flow and load rate, operated as follows:

- (1) Initially an arbitrary outflow rate profile is selected. To maintain consistency with the approach adopted for the control strategy, the profile is divided into a number of adjustment intervals corresponding to the number of control intervals in a 24-hour cycle.
- (2) The outflow rate profile, together with the inflow profile,

is used to calculate the tank hold-up (volume) response over the cycle. This hold-up profile, together with the influent flow rate and concentration profiles, enable the calculation of the effluent concentration profile and, in turn, the effluent load rate profile. The selected outflow rate profile and the associated effluent load rate profile then can be used to compute a measure of the equalization efficiency.

- (3) To determine the optimum outflow rate profile, an iterative procedure is followed whereby the effect of incremental changes in outflow rate at the different adjustment intervals is assessed by each time calculating the associated effluent load profile and the value of the equalization error. Changes to the profile which result in a decreased E_e value during the procedure are "accepted" until a change in flow rate (increase or decrease) at any of the adjustment intervals no longer improves the equalization efficiency. The final profile is then accepted as the optimum. Two different optimization techniques were used to check that this approach did, in fact, identify the optimal condition.

A necessary condition for the optimum outflow profile is that, under the influent pattern, the associated tank hold-up profile at no point exceeds the physical volumetric limits of the equalization tank, i.e. there is no overflow and/or emptying. It was found that this physical constraint could be incorporated as an integral part of the optimization procedure by adding a penalty error, E_{lm} , to the equalization error, E_e , which increases rapidly when the tank hold-up limits are exceeded, and then using the combined value as the objective function. In this way changes to the outflow profile which cause the hold-up limits to be exceeded at some point in the cycle will be strongly resisted because, even though the E_e component might decrease, the accompanying increase in E_{lm} will outweigh the decrease. To attain stability in this mechanism it was necessary to select an appropriate weighting factor, β , for the penalty error value, E_{lm} , so that the penalty error component in the objective function is negligible compared to the equalization component if the hold-up limits are

not exceeded; the inclusion of a weighting factor is merely a consequence of the units used in the calculation of the penalty error, E_{lm} .

Perhaps the principal benefit of the penalty error approach is that it prevents development of problems of mathematical discontinuities and instability in the iterative optimization procedure. This is explained best by an example: One manifestation of the approach is that *during* the procedure to identify the optimal solution it is possible that hold-up values outside the physical limits can be encountered in an interim solution - however, the penalty error "forces" the development of an optimal outflow rate profile with an associated hold-up profile that satisfies the physical limits. This transition from a physically-impossible solution to an acceptable one is mathematically continuous, with the advantage that problems of instability (which arise with methods that incorporate discontinuities to avoid unacceptable interim solutions) will be bypassed.

A further advantage of the volumetric penalty error approach is that the penalty error can be formulated to allow specification of upper and lower tank hold-up limits within the physical extreme values. This is useful for the analysis of situations where, for example, the tank hold-up may not drop below a specified level for some reason.

Application of the optimization procedure using the combined equalization error and the volumetric limit penalty error still gave rise to certain problems: with small equalization tanks (< 3 hours mean retention time), "spikiness" could develop in the outflow rate profile. One method of accounting for this problem would have been simply to specify a maximum allowable rate of change of outflow rate in the development of the optimum profile. However, to maintain consistency in the mathematical procedure, a second penalty error, E_s , was included in the objective function to constrain the *rate of change of tank outflow rate*; this ensures the development of a smooth profile. Large values of E_s in the objective function, while ensuring the development of a smooth outflow rate profile, will favour *flow* equalization, and will tend to mask the effect of the equalization error weighting factor, α (see Eq 9.2). To prevent this situation again it is necessary to include a weighting factor,

ω , for the penalty error, E_s , to maintain an appropriate balance between the magnitudes of the different components of the objective function.

To summarize, the objective function (or *error expression*) which was found to result in acceptable behaviour of the equalization algorithm was made up of three components, one of which (E_e) itself consisted of two parts, i.e.

$$\begin{aligned} E_t &= E_e + E_{lm} + E_s \\ &= \alpha E_f + (1-\alpha)E_{ld} + \beta E_{lm} + \omega E_s \end{aligned} \quad (9.5)$$

3.1 Application of the Equalization Algorithm

The results from application of the equalization algorithm under invariant daily input patterns potentially provided a very useful means for evaluating the effects of various parameters on equalization performance. For this purpose it was necessary to devise a method of assessment. One method of assessment is the qualitative (visual) approach in which the effluent flow and load rate patterns are compared with the influent patterns; this method is most useful but does not allow quantitative comparison. To obtain a quantitative comparison a numerical measure of the effectiveness of equalization was required. A suitable measure was found to be the *relative error*, E_r , defined as the ratio of the effluent equalization error, $(E_e)_1$, to the influent equalization error, $(E_e)_0$; the latter calculated on the same basis as the effluent error, but using the influent flow and load rate patterns i.e. Eqs 9.2, 9.3 and 9.4, with

$$E_r = (E_e)_1 / (E_e)_0 \quad (9.6)$$

The relative error approach was used to compare the behaviour of both in-line and side-line equalization configurations. The principal conclusions were:

- (1) For both in-line and side-line equalization, the efficiency of equalization increases with increasing tank size; however, the *rate* of improvement decreases with increasing size. Optimal equalization generally requires a tank

with a mean retention time (based on the mean inflow rate) in the region of 4 to 6 hours. Very little is gained in equalization efficiency for retention times greater than 6 hours.

- (2) Almost identical curves of relative error, E_r , versus retention time were obtained for influent data collected at different full-scale treatment plants, i.e. the efficiency of equalization with retention time for equalization facilities receiving influent flow and load rate patterns that differ substantially between plants appear to follow very similar trends.
- (3) An important characteristic exhibited by the controlled load rate is that, whereas the load rate in the uncontrolled (influent) cycle may fluctuate between a quarter and two to three times the mean (with consequential low and high oxygen demands in the downstream process), the controlled load is virtually constant, with a small *drop* once every 24 hours. This phenomenon will have a marked effect on aeration control, and will also substantially reduce the cost of providing aeration capacity to meet the peak requirement.
- (4) The behaviour of the algorithm over the region where there was a drop in effluent load rate (see 3 above) highlighted the superiority of the optimization approach over the subjective response action likely if the control decisions were by human agency. When the tank hold-up was approaching its lower limit the algorithm caused the outflow rate to *increase*, thereby increasing the rate at which the already low tank level was dropping - an action unlikely to be duplicated in manual control. The necessity for this, however, was evident from the objective (to equalize both flow and load): over this period the tank outflow rate was increased slightly to sustain the decreasing load rate.
- (5) With regard to equalization tank volume requirements, comparison of side-line and in-line equalization indicated that, in the region where effective equalization is achieved, both schemes require the same size of equalization tank,

i.e. neither scheme results in a decreased volume requirement over the other.

- (6) With side-line equalization as much as 60 percent of the daily inflow may bypass the equalization tank without reducing the equalization efficiency. This may allow a substantial saving in pumping costs where gravity flow through the tank is not possible. However, the disadvantage with side-line equalization is that the tank no longer acts as a buffer to all of the rapid fluctuations in the influent stream because part of the inflow bypasses the tank. Therefore, where possible in-line equalization should be used in preference to the side-line configuration.

A general conclusion regarding the equalization algorithm is that it provides an effective aid in establishing guide-lines for the design of equalization facilities. Furthermore, quantitization of the efficiency of the equalization solution for any particular equalization situation (influent patterns, configuration, size, etc) affords a rapid and simple method for selecting the most appropriate design for that situation.

Formulation of the *equalization algorithm* constituted the first phase in the development of the equalization control strategy. Once this aspect had been completed the next step was incorporation of the equalization algorithm in the control strategy structure outlined prior to development of the algorithm.

3.2 Control Strategy

In control strategy operation the equalization algorithm is applied at regular short intervals to determine the optimal outflow rate profile for an ensuing 24-hour cycle under the expected 24-hour input patterns. The *actual* tank outflow rate for the duration of the short (say, half-hour) control interval is set equal to the value at the start of the calculated optimum profile for the ensuing 24-hour cycle. By re-optimizing operation at regular short intervals to account for the variability of the influent patterns under real-time conditions, near-optimal operation on a continuous basis should be attained.

Successful operation of the control strategy obviously depends to a large degree on the ability to make accurate predictions, at the start of any control interval, of the expected influent flow and load rate patterns for the ensuing 24-hour cycle. Because the daily input patterns are repeated with relatively small variations from day to day, it was decided that the expected influent patterns should be based on the historical average influent patterns. It was found that, if the influent patterns are very similar from day to day, and if the patterns are close to the mean historical influent patterns, then the control strategy operates very successfully i.e. the daily outputs are very close to the optimal ones obtained under invariant daily inputs. However, if the daily inflow patterns differ substantially from the mean historical patterns, difficulties are encountered, particularly over those parts of the cycle when the tank is either near-full or near-empty. It was found that this problem can be overcome by basing the prediction primarily on the historical inflow and concentration data, but incorporating an adjustment to the inflow data based on differences between actual and historical inflow rates immediately prior to the prediction of the influent profiles for the ensuing 24-hour cycle.

A second problem encountered in the prediction of the expected 24-hour influent patterns based on the historical average patterns was that changes to the influent patterns (as a result of, for example, changes in the sewer collection network) may cause the historical data stored in the microcomputer memory no longer to conform to the daily inputs. To overcome this problem, a mechanism for continuous updating of the historical *inflow rate* data was incorporated in the strategy as follows:*

By monitoring the change in tank level over a control interval, and knowing the tank outflow rate, it was possible to compute the inflow rate, and in turn update the historical data stored in the microcomputer memory. In this way, a running average of historical data is maintained; this approach also allows the effect of

* Updating of historical influent concentration data is discussed later.

gradual seasonal changes in flow rate to be automatically incorporated in the operation.

Yet another problem in the prediction of expected 24-hour influent patterns was that the influent patterns differ substantially between weekday and weekend. An analysis of data for several treatment plants showed that the influent patterns for weekdays and weekend days differ sharply in (1) the form of the flow and load rate patterns and (2) a reduction in the mean daily flow and load rates for the weekends compared to weekdays. This problem was resolved by distinguishing between two types of historical daily inputs - one for weekdays and one for weekend days (and holidays). With this approach application of the control strategy showed that the strategy very effectively evens out the sharp disparity in flow and load rates in the transition from week to weekend, and *vice versa*. That is, the strategy allows the effect of the change to be spread over an extended period without necessitating any sudden control action.

Accepting that the expected influent profiles for an ensuing 24-hour cycle could be determined, application of the algorithm under real-time conditions (i.e. in the control strategy) nevertheless differs slightly from the application under invariant daily inputs - it became evident that the constraint on maintaining a material balance *over a 24-hour cycle* must not be imposed when the algorithm is applied under real-time conditions:

The objective in applying the equalization algorithm, for both invariant daily inputs or for real-time conditions, is to determine the 24-hour outflow rate profile which results in the maximum attenuation of influent flow and load variations, that is, the objective is to maintain the outputs as close as possible to the respective mean values of the expected 24-hour input patterns. In the analysis under invariant inputs, where the daily cyclic influent patterns are repeated identically from day to day, it was necessary to follow mass balance principles over a 24-hour cycle because the daily outflow necessarily equalled the daily inflow, and the tank situation (hold-up, concentration, outflow rate, etc) must be identical at the

start and end of each 24-hour cycle. Under real-time conditions, in view of the variability of the influent patterns, it is unlikely that the tank situation (hold-up, etc) corresponds identically to the optimal one indicated by the historical influent data at the time that the equalization algorithm is applied - in fact, if, say, a rainstorm has occurred then it is possible that the tank situation is very different from the optimum. Effective long-term operation of the strategy hinges on the expectation that the influent patterns in general will correspond relatively closely to the historical data. Therefore, even if the tank situation is non-optimal when the algorithm is utilized, the action of the strategy should be to endeavour to return the situation to optimality in future cycles (observing the volumetric limits and constraint on rate of change of outflow rate, of course). In order to achieve this action it is necessary to drop the requirement of maintaining a material balance during application of the algorithm; in this way, by allowing either more or less than the daily inflow to leave the tank over 24-hours it would be possible to converge to the optimal condition in future cycles.

Once the mass balance constraint had been dropped it was necessary to ensure that the control strategy would still lead to optimal operation. To this end the strategy was tested, assuming that the actual inputs corresponded exactly to the historical data, but with the starting condition different from the optimal one. It was found that, after one or two cycles, the operation returned to optimality - even though a mass balance was not imposed; once the behaviour had stabilized the daily outflow equalled the inflow and the tank situation was identical at corresponding times in subsequent daily cycles.

3.3 Testing the Control Strategy

To test the control strategy a series of simulations (using input data measured at full-scale treatment plants) was devised to check whether or not the conclusions obtained using the algorithm under

under invariant daily cyclic inputs still hold for the real-time situation. The results of these simulations indicated that:

- In all cases the conclusions (with regard to tank size, configuration, etc) obtained under fixed diurnal input patterns also hold under real-time inputs.
- There is only a marginal decrease in performance efficiency with the real-time daily inputs compared to the invariant inputs.

The final phase of evaluation of the control strategy involved testing the behaviour under unusual input patterns. The purpose of this part of the study was to illustrate that, under certain circumstances, situations may arise where emergency action must supercede the action of the control strategy; two examples of such situations were considered:

- (1) Minimum level requirement: In certain cases it may be obligatory that the tank level does not drop below some absolute minimum value. An example would be the situation where floating aerators are used to mix the tank contents, and a minimum operating depth is specified. It was found that this condition could be satisfied by monitoring tank level at short intervals (of, say, 5 minutes); if the level drops to below a specified minimum, the outflow rate is reduced to that of the inflow - once the level returns to within acceptable limits the outflow rate is re-set to the optimum value specified by the equalization algorithm.
- (2) Storm conditions: The control strategy was developed for systems with separate sewers and stormwater drains; however, even with separate systems, a certain flow of stormwater may be expected to enter the sewers during, and after, a rainstorm. To test the behaviour of the control strategy under such conditions four possible situations were considered: either a "small" or a "large" storm superimposed on the usual input pattern, occurring either during the period of minimum or maximum inflow in

the daily cycle.* This aspect of the study yielded three principal conclusions:

- A "small" storm has little effect on the normal operation, irrespective of when it occurs in the daily cycle.
- A "large" storm, occurring during the period of minimum inflow can be readily accommodated; the strategy utilizes the available tank hold-up capacity to distribute the excess inflow over an extended period, with only a marginal decrease in equalization performance - this is possible because the tank is near-empty during the period of minimum inflow.
- A "large" storm, if it occurs during the peak flow period, when the tank is near-full, can result in a deterioration in performance because there is no capacity available to store the excess flow. The nett effect is that the effect of the storm flow is damped only partially.

4. IMPLEMENTATION OF THE CONTROL STRATEGY

For the implementation of flow equalization the only requirements needed to operate the microcomputer control strategy are the facilities to:

- measure liquid level in the tank
- measure tank outflow rate
- specify the setpoint for the outflow rate controller.

These measurements can all be obtained with very reliable, and simple, instrumentation which is stable in the long term - an important aspect in the South African context, to minimize back-up needs.

For implementation of simultaneous flow and *load* equalization it would appear that continuous monitoring of, say, COD concentration would also be required. This would pose a problem because instrumentation

* The extra volume entering the tank as the result of a storm was assumed to be 10 per cent and 40 per cent of the total daily inflow for the "small" and "large" storms respectively.

required to monitor COD on a continuous basis, and the operation thereof, is both complex and costly — this would nullify, to a degree, the objective of developing a cheap and simple alternative to in-plant control. However, continuous monitoring of COD was *not* found to be necessary; it would be sufficient to check the historical COD data stored in the microcomputer memory at intervals of, say, 3 to 4 months. This is so because simulation studies indicated that the system response is relatively insensitive to deviations in actual influent concentration from the historical data for the magnitude of deviation normally encountered. The reason for this insensitivity arises from the fact that the load rate is the product of flow rate and concentration; because the flow rate is accurately accounted for continuously, deviations in concentration affect the load rate only in part. Indeed, the added efficiency in load equalization obtained by continuous COD monitoring is most unlikely to merit the cost of implementation.

The control strategy was implemented on the 100 Ml.d^{-1} Goudkoppies plant which has an in-line equalization tank with a mean retention time of approximately 4, 5 hours. This tank is not stirred so that it was not possible to apply the CSTR equations for COD concentration (and load) with any expectation of accuracy. Consequently, in this instance, only the *flow* equalization aspect of the control strategy was implemented (i.e. $\alpha = 1$ in Eq. 9.1).

On start-up the control strategy behaved exactly according to specification; initially the tank outflow rate was not as constant as would be expected with a tank of this size, but this was due to differences between the roughly estimated historical inflow rate data and the actual influent patterns. However, within a few days the initial historical inflow profiles had been updated to reflect the actual influent patterns more accurately and the control strategy operated with remarkable effectiveness:

- (1) During the mid-week period the tank outflow rate was maintained very near constant.
- (2) The strategy handled the transition from week to weekend, and *vice versa*, in the expected manner by spreading the effect of the step change in daily inflow rate over an extended period.

- (3) The control strategy removed a considerable work load from the plant operators.
- (4) The level of equalization efficiency was incomparably higher than that attained when the outflow rate was specified manually.

In the case of the implementation at Goudkoppies initial indications are that, even though the tank is un-mixed, the degree of load equalization achieved perhaps exceeds that expected for a completely mixed tank. In particular, when the tank level is low, the drop in load rate does not appear to be as great as that encountered in simulations for a completely mixed tank. It can perhaps be surmised that the load rate is partially sustained over this period by solids being flushed out, having settled on the tank base during the remainder of the cycle. This behaviour is possibly specific to the Goudkoppies installation — the tank contains a set of dwarf-walls laid out in such a way that, when the tank level is low, flow is canalized in series fashion and settled solids are scoured from the tank as a result of the increased linear flow velocity along the tank flow. Because of this feature it would be inappropriate to draw any general conclusions as yet on the merits of using an un-mixed tank.

5. CLOSURE

In this investigation the original objective was to develop a practical procedure, or control strategy, by means of which an equalization tank can be operated to give the minimum variation in flow and load rate under the normal cyclic inputs encountered at wastewater treatment plants. Now that the investigation has been concluded one may enquire to what extent the objective has been satisfied.

From both a theoretical and experimental point of view there seems to be no doubt that the proposed control strategy gives rise to a very satisfactory performance of equalization tanks. The success achieved in this project is likely to lead to added interest in equalization, particularly for the South African situation where control of nutrient removal plants (operated at long sludge ages) is important and installation of high performance equalization tanks will obviate most of the difficulties encountered in the application of in-plant control procedures.

This investigation has been directed specifically towards the development of a high quality scheme; this demanded the inclusion of a micro-computer and electronic circuitry. Implementation of the control strategy undoubtedly requires the attention of an electronics/micro-computer control system expert. However, once a system is installed, the simple nature of the measuring instrumentation and the robustness and long-term reliability of modern microcomputers makes that maintenance problems should be minimal, particularly if high quality components are used in the monitoring equipment and for the electronic circuiting.

Apart from the control of nutrient removal plants, installation of equalization facilities on other plant-types will allow increased plant capacity and simplified plant control. This would apply particularly to extended aeration plants where, due to the long sludge ages normally employed, the oxygen demand fluctuates appreciably. For these plants, because over-aeration is not such a critical factor as in nutrient removal plants, even partial equalization will be sufficient to allow an increase in plant capacity. In such cases, the high degree of efficiency attained with the computer-based control strategy perhaps is not necessary — partial equalization should be sufficient. Partial equalization is likely to be possible using some form of mechanical control scheme. This investigation into equalization should provide the background for the development of such a scheme, and opens up a field for future research that may yield results of great value, particularly to small isolated communities.

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A P P E N D I X A.

INFLUENT FLOW/CONCENTRATION DATATable A.1 Hourly Flow Data from Monday 14/3/77 until Sunday 20/3/77
for the Cape Flats Sewage Works, Cape Town

Time	Flow Rate (Ml/d)						
	Mon.	Tues.	Wed.	Thurs.	Fri.	Sat.	Sun.
00h00		58,3	43,2	43,2	42,2	39,0	48,5
01h00		54,0	44,2	45,0	42,3	38,5	42,3
02h00		48,5	45,0	44,2	42,3	40,3	37,0
03h00		37,3	43,1	42,3	40,4	40,0	10,0
04h00		10,0	40,0	38,6	40,1	37,4	52,0
05h00		52,7	30,0	25,0	38,5	36,5	10,0
06h00		25,0	24,0	20,0	10,0	32,0	20,1
07h00	15,0	27,3	23,4	22,5	20,1	46,0	27,4
08h00	18,3	25,5	25,0	24,1	24,0	24,0	32,1
09h00	23,5	24,0	27,8	23,4	24,0	21,0	17,3
10h00	23,1	25,0	28,3	25,0	24,0	23,0	21,2
11h00	21,3	26,0	27,5	24,0	22,6	25,0	56,5
12h00	21,0	50,0	28,3	25,5	46,7	22,0	32,0
13h00	83,1	52,5	85,0	49,6	45,0	47,5	47,6
14h00	76,2	88,0	81,2	82,4	77,3	47,0	55,0
15h00	75,3	82,0	73,4	80,1	82,2	76,5	53,3
16h00	77,0	79,3	71,3	80,1	84,0	57,6	53,8
17h00	73,8	78,2	77,4	82,3	80,2	55,0	73,4
18h00	75,0	76,0	78,6	76,9	83,3	55,0	70,0
19h00	74,0	73,2	12,7	77,6	80,1	56,0	58,9
20h00	81,0	72,8	72,4	75,0	72,4	54,1	56,6
21h00	81,0	79,0	70,0	78,1	68,1	54,8	40,0
22h00	75,0	76,2	71,3	65,0	67,7	52,2	40,0
23h00	40,0	40,0	61,0	38,5	57,2	50,0	41,3
24h00	58,3	43,2	43,2	42,2	39,0	48,5	35,6

Table A.2 Averaged Hourly Flow Data for the Period Monday 14/3/77 to Friday 18/3/77 for the Cape Flats Sewage Works, Cape Town

Time	Average Flow Rate (Mℓ/d)	Typical COD Concentration (mg COD/ℓ)
00h00	41,8	830
01h00	46,4	842
02h00	45,0	844
03h00	40,8	1182
04h00	32,2	912
05h00	36,6	809
06h00	19,8	769
07h00	21,7	681
08h00	23,4	672
09h00	24,5	559
10h00	25,1	713
11h00	24,3	503
12h00	34,3	424
13h00	63,0	638
14h00	81,0	687
15h00	78,6	548
16h00	78,3	1141
17h00	78,4	901
18h00	78,0	1071
19h00	75,5	923
20h00	74,7	1068
21h00	75,2	976
22h00	71,0	1163
23h00	47,3	839
24h00	45,2	826

Table A.3 Hourly Flow and Concentration Data from "Smoothing"
Observed Average Flow Profile and a Typical Concentration
Profile (Cape Flats)

Time	Flow Rate (Mℓ/d)	COD Concentration (mg COD/ℓ)
00h00	44,0	860
01h00	43,5	860
02h00	42,2	860
03h00	40,0	860
04h00	36,2	860
05h00	30,0	810
06h00	20,0	760
07h00	20,6	710
08h00	21,2	660
09h00	21,8	610
10h00	22,4	560
11h00	23,0	510
12h00	45,0	460
13h00	64,0	595
14h00	81,0	730
15h00	80,0	865
16h00	79,0	1000
17h00	78,0	1000
18h00	77,0	1000
19h00	76,0	1000
20h00	75,0	1000
21h00	74,0	1000
22h00	73,0	1000
23h00	44,0	860
24h00	44,0	860

Table A.4 Goudkopries Raw Influent Data for Period 4/8/79 to 11/8/79

Q = Influent flow rate (M ³ /d) S _{ti} = Influent COD concentration (mg COD/L) M _{COD} = Influent mass loading rate (kg COD/d*10 ⁻³)																					
TIME	SUNDAY			MONDAY			TUESDAY			WEDNESDAY			THURSDAY			FRIDAY			SATURDAY		
	Q	S _{ti}	M _{COD}	Q	S _{ti}	M _{COD}	Q	S _{ti}	M _{COD}	Q	S _{ti}	M _{COD}	Q	S _{ti}	M _{COD}	Q	S _{ti}	M _{COD}	Q	S _{ti}	M _{COD}
00h00	45,8	530	24,3	60,5	430	26,0	77,8	940	73,1	77,8	950	73,9	77,8	750	58,3	103,7	1200	124,4	51,9	1100	57,0
02h00	43,2	550	23,8	51,8	350	18,1	64,8	420	27,2	51,8	440	22,8	43,2	780	33,7	51,8	1500	77,8	47,5	880	41,8
04h00	36,3	500	18,1	38,9	440	17,1	43,2	960	41,5	51,8	910	47,2	43,2	660	28,5	38,9	1550	60,3	43,2	700	30,2
06h00	51,8	550	28,5	38,9	177	6,9	51,8	730	37,8	43,2	450	19,4	43,2	720	31,1	43,2	1400	60,5	38,9	550	21,4
08h00	51,8	500	25,9	86,4	150	13,0	86,4	710	61,3	51,8	460	23,8	138,2	240	33,2	82,1	1300	106,7	51,8	360	18,7
10h00	86,4	500	43,2	172,8	230	39,7	155,5	270	42,0	121,0	540	65,3	155,5	1000	155,5	129,6	550	71,3	103,7	230	23,8
12h00	112,3	460	51,7	129,6	920	119,2	164,2	930	152,7	129,6	880	114,0	138,2	800	110,6	164,2	520	85,4	103,7	880	91,2
14h00	86,4	510	44,1	155,5	700	108,9	129,6	970	125,7	181,4	680	123,4	164,2	1300	213,4	146,9	460	67,6	121,0	1200	145,2
16h00	77,8	310	24,1	138,2	840	116,1	138,2	980	135,5	129,6	660	85,5	146,9	1200	176,3	138,2	460	63,6	121,0	880	106,4
18h00	73,4	300	22,0	121,0	930	112,5	112,3	960	107,8	129,6	650	84,2	129,6	1100	142,6	95,0	680	64,6	73,4	710	61,3
20h00	69,1	530	36,6	86,4	940	81,2	112,3	980	110,1	103,7	670	69,5	112,3	1700	190,9	86,4	730	63,	95,0	620	58,9
22h00	69,1	490	33,9	86,4	880	76,0	95,0	950	90,3	103,7	610	63,2	103,7	980	101,6	77,8	710	55,2	129,6	550	47,5
24h00	60,5	430	26,0	77,8	940	73,1	77,8	950	73,9	77,8	750	58,3	103,7	1200	124,4	51,8	1100	57,0	112,3	530	59,5
MEAN	66,5	-	30,9	95,7	-	62,1	100,7	-	83,0	96,4	-	65,4	107,7	-	107,7	93,0	-	73,7	84,1	-	58,7

MEANS	FLOW	LOAD
Whole week	92,0	68,8
Weekday	98,7	78,4
Weekend day	75,3	44,8

Mean weekend flow = 76,3% of weekday mean
Mean weekend load = 57,1% of weekday mean

Table A.5 Goudkoppies Averaged Hourly Data for Period (Monday to Friday) 5/8/79 to 19/8/79

	Before Balancing		
	Q, Mℓ/d	COD,mg/ ℓ	Load, kg/d*10 ⁻³
00h00	78,6	921	72,4
01h00	66,0	860	56,8
02h00	52,7	698	36,8
03h00	48,0	840	40,3
04h00	43,2	904	39,1
05h00	41,5	832	34,5
06h00	44,1	750	33,1
07h00	57,5	655	37,7
08h00	89,0	572	50,9
09h00	135,0	529	71,4
10h00	146,9	518	76,1
11h00	145,8	690	100,6
12h00	145,2	810	117,6
13h00	151,4	818	123,8
14h00	155,5	822	127,8
15h00	148,6	825	122,6
16h00	138,2	828	114,4
17h00	126,0	844	106,3
18h00	117,5	864	101,5
19h00	108,3	965	104,5
20h00	100,2	1004	100,6
21h00	96,1	972	93,4
22h00	93,3	826	77,1
23h00	87,5	878	76,8
24h00	78,6	921	72,4

A P P E N D I X B

COMPUTER PROGRAMS FOR EQUALIZATION ALGORITHMB.1 TANK OUTFLOW PROFILE DEVELOPMENT ALGORITHM PROGRAMB.1.1 General Description

TOPDA (Tank Outflow Profile Development Algorithm) is an ASCII FORTRAN computer program which uses an iterative optimization technique to develop the outflow profile from a tank of a specific size in an equalization facility in such a manner that the optimum attenuation of the effluent flow and load profiles is achieved. The objective function in the optimization is an error expression which takes into account the attenuation of effluent flow and load from the equalization installation as well as the physical constraints of the system (Section 4, Chapter 3).

The workings of the program are presented by means of a flowchart (Figs. 3.4 (a), (b) and (c)), the contents of which are amplified by Figs. 3.4 (d) and (e).

Numerical results from the program are presented and discussed in Chapters 3 and 4.

A detailed description of the internal logic of the program will not be presented here. TOPDA is written in modular form; that is, it consists of a main program and a series of independent subroutines. The function of the main program is to read the necessary input information and to call the relevant subroutines which perform the actual optimization and output.

Amongst the general features of the program are the following:

- (a) All arithmetic is performed in single precision.
- (b) Certain printed output is optional. The user may select the frequency of data output during the iterative optimization by entering the relevant option in the data input.
- (c) The program is designed for interactive use on a computer terminal. When the program is executed it calls for the required data input which is supplied by the user.

- (d) Once the correct data is received by the program the method of optimization can be selected (Section 3.3, Chapter 3). The number of iterations to be performed using this selected optimization method, and the allowable change in tank outflow rate at the end of each improvement interval is then specified by the user.
- (e) During execution of the program the method of optimization can be changed.
- (f) In addition to the output supplied during execution, the results of the optimization are written to temporary files on completion of execution. This facilitates using the results for graphical output.
- (g) Computer storage allocation can be adjusted according to the size of the problem by changing the dimensions of certain arrays at the head of the main program and each subroutine.
- (h) All data input is in free format.

A detailed description of the data input, with sample data, and execution of the program is given in Section B.1.2.

B.1.2 A Typical Runstream for TOPDA

An example of the execution of TOPDA is laid out below.

It is assumed that the program is contained in the element CMASP*EQUAL.TOPDA. The program must be compiled and mapped before the first execution as follows:

```
@ FTN  CMASP*EQUAL.TOPDA
@ EOF

@ MAP  CMASP*EQUAL.TOPDAM,.TOPDAM
@ EOF
```

The element CMASP*EQUAL.TOPDAM contains the following

```
IN  CMASP*EQUAL.TOPDA
LIB SYS$*FTNLIB$.
```

It is assumed that information concerning the nature of the influent flow and concentration has been obtained, and that the elements CMASP*EQUAL.CAPEFIN and .CAPEBIN each contain 49 half-hourly point values of influent flow rate and concentration respectively. The 1st and 49th values in each element, corresponding to the information at 00h00 and 24h00 should be the same. Any units of flow rate can be used, while the units of concentration should be mg COD/l or mg BOD/l.

The following runstream is used to access and execute TOPDA

```
@ RUN
@ PASSWD
@ ASG, AX  CMASP*EQUAL.
@ XQT  CMASP*EQUAL.TOPDAM
```

At this point the program calls for input of data and the user is required to provide certain responses

```
*****
TANK OUTFLOW PROFILE DEVELOPMENT PROGRAM
      DATA INPUT
      (ALL DATA IN FREE FORMAT)
*****
```

Input 1:

```
ENTER EQUALIZATION CONFIGURATION OPERATING MODE
ITYPE
  = 1 FOR FLOW SPLITTING
  = 2 FOR FLOW TOPPING
  = 1 OR 2 FOR IN-LINE EQUALIZATION
```

>1

The user is required to respond with the code for the mode of operation of a side-line equalization installation. In the case of in-line equalization either a 1 or a 2 is entered.

Input 2:

```
ENTER VALUE OF FLOW DIVISION FACTOR
GAMMA
E.G. 0.40
```

>0.30

The user enters the value of the flow division factor. In the case of in-line equalization enter 0.00.

Input 3:

ENTER TANK RETENTION TIME BASED ON THE
AVERAGE INFLUENT FLOW (HOURS)

THI

E.G. 5.00

>6.00

Input 4:

ENTER UPPER AND LOWER ALLOWABLE TANK
VOLUME LIMITS (%)

TOPLIM BOTLIM

E.G. 95.0 5.0

>100.0 0.0

Input 5:

ENTER ERROR CRITERION WEIGHTING FACTORS

ALPHA BETA ZETA

E.G. 0.50 2.0E-06 20.0

>0.50 2.0E-06 100.0

The choice of values of the weighting factors for the error term is discussed in Section 6 of Chapter 3.

Input 6:

ENTER THE NUMBER OF SIMULATION INTERVALS AND THE
NUMBER OF IMPROVEMENT INTERVALS PER HOUR.

NUMS NUMC

E.G. 12 2

>12 2

NUMS and NUMC are, respectively, the number of simulation intervals per hour and the number of improvement intervals per hour. The graphical results shown in Chapter 4 were all obtained using values of 12 and 2 for NUMS and NUMC, respectively. That is, 5 minute integration intervals were used, while adjustments to the tank outflow profile were made over 30 minute intervals. In the computation it is necessary to dimension certain arrays of size $(NUMC*24 + 1)$ and other arrays of size $(NUMS*24 + 1)$. This was done by way of PARAMETER statements at the head of each subprogram. It was found that for tank retention times of 3 hours or more, values of 12 and 2 for NUMS and NUMC, respectively, gave satisfactory results. For tank hold-ups of less than 3 hours values of 12 and 2 lead to some instability in the calculation procedure, and it was necessary to increase the values of NUMS and NUMC to 24 and 3, respectively. This increases both the computation time and the program storage requirement as the values of the PARAMETER statements at the head of each subprogram must be increased. However, apart from the necessity for completion in presenting the results in this report it is unlikely that users will require utilizing the program for tank hold-ups of less than 3 hours. Thus, the suggested values of NUMS and NUMC of 12 and 2 per hour, respectively, can be adhered to.

Input 7:

```
ENTER THE FREQUENCY OF PRINTING OUTPUT
NOPRT
E.G. 4
```

>1

NOPRT specifies the frequency at which intermediate results are output. A value of 2 means that results are printed every 2nd cycle during the optimization.

Input 8:

@ADD ELEMENT CONTAINING 49 HALF-HOURLY
POINT VALUES OF INFLUENT FLOW (ANY UNITS)

>@ADD EQUAL.CAPEFIN

Input 9:

@ADD ELEMENT CONTAINING 49 HALF-HOURLY
POINT VALUES OF INFLUENT CONCENTRATION

>@ADD EQUAL.CAPEBIN

Input 10:

GIVE A STARTING VALUE FOR TANK VOLUME (%)

>96.0

At this point the program supplies the fractional division of the flow between the stream diverted to the tank and the stream passing directly to the downstream process. Here we have a side-line equalization installation with a flow division factor of 0,30 so the division is obvious.

FRACTIONAL FLOW APPORTIONMENT
DIRECT TO PROCESS = .300
VIA EQUAL. TANK = .700

Input 11:

```
WHAT METHOD OF OPTIMIZATION DO YOU WANT?  
STEEPEST DESCENT/FAST CONVERGENCE (SD/FC)  
>SD
```

The user selects the method of optimization to be used by entering either SD or FC for optimization by the Method of Steepest Descent or the Fast Convergence technique, respectively.

Input 12:

```
HOW MANY ITERATIONS? WHAT LIMIT FOR FLOW ADJUSTMENT?  
>3 .02
```

The user specifies how many cycles are to be performed using the selected optimization method, and also the amount by which the flow at the end of each improvement interval should be adjusted.

All the results presented in Chapter 4 were obtained, using the Fast Convergence optimization technique, as follows:

- (i) An initial value of LIMIT of 0,02 was used until DELTA ERROR became zero.
- (ii) Execution was continued with a value of LIMIT of 0,01 until DELTA ERROR once again became zero.
- (iii) Execution was completed.

It is suggested that the user will find this approach to give acceptable results.

The program provides limited output every NOPRT cycles as follows:

TWO-HOURLY PCV VALUES

96.0 92.6 87.6 77.7 63.9 50.7
40.5 46.6 60.3 73.0 84.8 95.7
96.0

PCVMAX = 97.75

E(FINAL) = .255665-001 DELTA ERROR = -.100000+021

FBAR = .999999+000 LBAR = .857768+003

NO. OF ITERATIONS = 1

LAST ADJUSTMENT AT INTERVAL 48

AVERAGE ERROR DISTRIBUTION

FLOW = .899284-002

FLOW+LOAD ERROR = .254955-001

LOAD = .165027-001

MIN/MAX PENALTY = .246860-004

DF/DT PENALTY = .463000-004

TWO-HOURLY PCV VALUES

96.2 92.8 87.7 77.8 64.0 50.8
40.5 46.6 60.3 73.0 84.9 95.9
96.2

PCVMAX = 97.92

E(FINAL) = .253699-001 DELTA ERROR = -.196597-003

FBAR = .999999+000 LBAR = .857787+003

NO. OF ITERATIONS = 2

LAST ADJUSTMENT AT INTERVAL 40

AVERAGE ERROR DISTRIBUTION

FLOW = .890519-002

FLOW+LOAD ERROR = .252412-001

LOAD = .163360-001

MIN/MAX PENALTY = .361135-004

DF/DT PENALTY = .925975-004

Each set of output shows:

- (i) Thirteen tank hold-up (PCV) values, expressed as a percentage of total tank volume, at two-hourly intervals, as well as the maximum value (PCVMAX).
- (ii) E(FINAL), the value of the error term at the end of the cycle, with DELTA ERROR, the change in error since the last cycle.

- (iii) FBAR and LBAR, the mean values of flow and load in the effluent. FBAR should be 1,0.
- (iv) The number of cycles which have been completed, and the interval at which the last adjustment to the tank outflow profile was made. (There are $24 \times \text{NUMC}$ intervals over a day). The interval of last adjustment will always be 0 when the Fast Convergence optimization technique is used.
- (v) The individual components of the total error.

Execution of the program continues until either the specified number of cycles has been completed or the value of DELTA ERROR is zero. In the case of the latter it means that the value of E(FINAL) from the previous cycle is the minimum for the chosen value of LIMIT.

At this point the steps Input 11 and Input 12 are repeated with a new value for LIMIT.

B.1.3 Output of Program Results to Temporary Files

On completion of execution certain results are written to temporary files in order to provide the necessary information for the graphical representation of the results. Each temporary file contains $(\text{NUMS} \times 24 + 1)$ data values at $(60/\text{NUMS})$ minute intervals over the day. With NUMS equal to 12 as suggested this corresponds to 289 values: that is, point values at 5 minute intervals over the day with the first and the last value being equal.

The procedure for transferring data from, for example, a temporary file, 16., to an element in a program file, EQUAL.LOUTTANK, is as follows:

```
@ COPY, I 16., EQUAL.LOUTTANK
@ ED  EQUAL.LOUTTANK, .LOUTTANK
EXIT
```

Table B.1, below, lists the numbers assigned to the temporary files with their contents.

Table B.1 Contents of Temporary Files on Completion of Execution of TOPDA

File No.	Contents
15.	Flow rate of stream diverted to tank
16.	Total effluent mass load
17.	Tank hold-up (as a per cent of total tank volume)
18.	Tank effluent flow rate
19.	Tank effluent concentration
20.	Installation exit flow rate
21.	Installation exit concentration
22.	Total influent flow rate
23.	Total influent mass loading
24.	Flow rate of stream direct to process

B.1.4 Listing of Program TOPDA

CMASP*EQUAL(1).TOPDA

```

1      C*****
2      C
3      C    MAINLINE EQUALISATION PROGRAM
4      C    -----
5      C
6      C    THIS PROGRAM:
7      C      (1) READS IN THE INFLUENT FLOW AND CONCENTRATION DATA
8      C      (2) READS IN THE PROCESS INFORMATION AND IDENTIFIES
9      C          THE CONFIGURATION
10     C      (3) CALCULATES THE INPUTS OF FLOW AND CONCENTRATION
11     C          TO THE DIFFERENT PROCESS STREAMS.
12     C      (4) ATTEMPTS TO LESSEN THE OUTFLOW VARIATION IN FLOW AND
13     C          LOAD BY ALTERING THE DAILY TANK OUTFLOW PROFILE.
14     C      (5) FOR EACH IMPROVEMENT INTERVAL OUTFLOW FROM THE TANK IS
15     C          EITHER INCREASED, DECREASED OR NOT CHANGED.
16     C      (6) FOR EACH CHANGE IN OUTFLOW SUBROUTINES NEWPCV AND
17     C          ERCALC ARE CALLED.
18     C      (7) LIMITED OUTPUT IS GIVEN AT THE END OF EACH ITERATION.
19     C
20     C    VARIABLE LIST
21     C
22     C    ALPHA = WEIGHTING FACTOR FOR EQUALIZATION ERROR
23     C    BETA  = WEIGHTING FACTOR FOR VOLUMETRIC LIMITS PENALTY ERROR
24     C    BEXIT = CONCENTRATION OF MIXED STREAM
25     C    BIN   = CONCENTRATION OF INFLOW
26     C    BINIT = CONCENTRATION OF INFLOW (HALF-HOURLY VALUE)
27     C    BOTLIM = LOWER ALLOWABLE LIMIT OF PCV
28     C    BOUT  = EQUALIZATION TANK EXIT CONCENTRATION
29     C    DELT  = NO. OF SIMULATION POINTS PER IMPROVEMENT INTERVAL
30     C    E     = TOTAL ERROR VALUE
31     C    EDIF  = PENALTY ERROR FOR RATE OF CHANGE OF FLOW
32     C    EFLOD = SUM OF APPORTIONED FLOW AND LOAD ERROR
33     C    EFLOW = PORTION OF EFLOD DUE TO FLOW
34     C    ELOAD = PORTION OF EFLOD DUE TO LOAD
35     C    ELIM  = VOLUMETRIC LIMITS PENALTY ERROR
36     C    ERDIF = CHANGE IN ERROR OVER THE PRECEDING CYCLE
37     C    FBAR  = AVERAGE OF UNNORMALIZED INFLOW VALUES
38     C    FEXIT = MIXED EXIT STREAM FLOW
39     C    FIN   = INFLOW RATE
40     C    FINIT = INFLOW RATE (HALF-HOURLY VALUE)
41     C    FINSTR = INFLOW RATE DIRECT TO PROCESS
42     C    FINTNK = INFLOW RATE VIA EQUALIZATION TANK
43     C    FOUT  = OUTFLOW RATE FROM EQUALIZATION TANK
44     C    FDUIT = TEMPORARY ARRAY OF TANK OUTFLOWS
45     C    GAMMA = FACTOR FOR DIVISION OF INFLOW
46     C    ITER  = NO. OF IMPROVEMENT INTERVALS
47     C    ITYPE = FLAG TO IDENTIFY FLOW CONFIGURATION
48     C          = 1  FLOW SPLITTING
49     C          = 2  FLOW TOPPING
50     C    LAST  = NO. OF SIMULATION POINTS
51     C    LBAR  = MEAN OF LOUT VALUES
52     C    LIMIT = SIZE OF FLOW ADJUSTMENT OVER AN IMPROVEMENT INTERVAL
53     C    LIN   = INFLUENT LOAD (FLOW*CONCENTRATION)
54     C    LOUT  = MIXED EXIT STREAM LOAD
55     C    NCYC  = NO. OF CYCLES TO BE PERFORMED
56     C    NOPRT = NO. OF CYCLES BETWEEN PRINTING RESULTS

```



```

57      C      NUMC   = NO. OF IMPROVEMENT INTERVALS PER HOUR      C
58      C      NUMS   = NO. OF SIMULATION INTERVALS PER HOUR      C
59      C      PCV    = PERCENTAGE OF TOTAL TANK VOLUME            C
60      C      PCVMAX = MAXIMUM PCV VALUE OVER THE DAY             C
61      C      PCVT   = TEMPORARY ARRAY OF TANK PCV VALUES        C
62      C      SIGN   = DIRECTION OF ADJUSTMENT OF FLOW            C
63      C              = +1 INCREASE IN FLOW                       C
64      C              = -1 DECREASE IN FLOW                       C
65      C      THT    = EQUALIZATION TANK RETENTION TIME           C
66      C      TOPLIM = UPPER LIMIT OF PCV                         C
67      C      ZETA   = WEIGHTING FACTOR FOR RATE OF CHANGE OF TANK OUTFLOW C
68      C              RATE PENALTY ERROR                         C
69      C
70      C*****
71      C      PARAMETER N=300
72      C      PARAMETER M=50
73      C      CHARACTER REDO*1(9)
74      C      REAL LOUT,LBAR,LIMIT,LIN,LSUM
75      C      INTEGER STOP,DELT,SIGN,FINAL
76      C      DIMENSION FIN(N),FOUT(N),BIN(N),BOUT(N),LIN(N),
77      C      +PCV(N),E(M),SIGN(M),FINIT(M),BINIT(M)
78      C      DIMENSION FINSTR(N),FINTNK(N)
79      C      DIMENSION FEXIT(N),BEXIT(N),PCVT(N),FOUTT(N),LOUT(N)
80      C      CALL UNDSSET(3)
81      C      CALL DIVSET(3)
82      C      CALL OVFSSET(3)
83      C      CALL OVUNFL(3)
84      C      50  FORMAT( )
85      C      51  FORMAT(///'*****'
86      C      1/    ' TANK OUTFLOW PROFILE DEVELOPMENT PROGRAM'
87      C      2/    '          DATA INPUT'
88      C      3/    '          (ALL DATA IN FREE FORMAT)'
89      C      4/    '*****')
90      C      52  FORMAT(///' ENTER EQUALIZATION CONFIGURATION OPERATING MODE'
91      C      1/    ' ITYPE'
92      C      2/    '      = 1 FOR FLOW SPLITTING'
93      C      3/    '      = 2 FOR FLOW TOPPING'
94      C      4/    '      = 1 OR 2 FOR IN-LINE EQUALIZATION'//)
95      C      53  FORMAT(///' ENTER VALUE OF FLOW DIVISION FACTOR'
96      C      1/    ' GAMMA'
97      C      2/    ' E.G. 0.40'//)
98      C      54  FORMAT(///' ENTER TANK RETENTION TIME BASED ON THE'
99      C      1/    ' AVERAGE INFLUENT FLOW (HOURS)'
100     C      2/    ' THT'
101     C      3/    ' E.G. 5.00'//)
102     C      55  FORMAT(///' ENTER UPPER AND LOWER ALLOWABLE TANK'
103     C      1/    ' VOLUME LIMITS (%)'
104     C      2/    ' TOPLIM BOTLIM'
105     C      3/    ' E.G. 95.0 5.0'//)
106     C      56  FORMAT(///' ENTER ERROR CRITERION WEIGHTING FACTORS'
107     C      1/    ' ALPHA BETA ZETA'
108     C      2/    ' E.G. 0.50 2.0E-06 20.0'//)
109     C      57  FORMAT(///' ENTER THE NUMBER OF SIMULATION INTERVALS AND THE'
110     C      1/    ' NUMBER OF IMPROVEMENT INTERVALS PER HOUR.'
111     C      2/    ' NUMS NUMC'
112     C      3/    ' E.G. 12 2'//)
113     C      58  FORMAT(///' ENTER THE FREQUENCY OF PRINTING OUTPUT'
114     C      1/    ' NOPRT'

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115      2/          ' E.G. 4'//)
116      59      FORMAT(/// @ADD ELEMENT CONTAINING 49 HALF-HOURLY'
117      1/          ' POINT VALUES OF INFLUENT FLOW (ANY UNITS)'//)
118      61      FORMAT(/// @ADD ELEMENT CONTAINING 49 HALF-HOURLY'
119      1/          ' POINT VALUES OF INFLUENT CONCENTRATION'//)
120      C
121      C      READ IN DATA AND VARIABLES
122      C
123      WRITE(5,51)
124      WRITE(5,52)
125      READ(8,50) ITYPE
126      WRITE(5,53)
127      READ(8,50) GAMMA
128      WRITE(5,54)
129      READ(8,50) THT
130      WRITE(5,55)
131      READ(8,50) TOPLIM,BOTLIM
132      WRITE(5,56)
133      READ(8,50) ALPHA,BETA,ZETA
134      WRITE(5,57)
135      READ(8,50) NUMS,NUMC
136      WRITE(5,58)
137      READ(8,50) NOPRT
138      C
139      C      TO INITIALIZE SOME ARRAYS
140      C
141      NCYC=1
142      DELT=NUMS/NUMC
143      STOP=NUMC*24
144      ITER=STOP
145      FINAL=STOP+1
146      DO 40 I=1,STOP
147      SIGN(I)=1
148      40      E(I)=1.0E20
149      E(FINAL)=1.0E20
150      LAST=NUMS*24+1
151      STOP=LAST-1
152      C
153      C      READ 49 HALF-HOURLY POINT VALUES
154      C      OF INFLUENT FLOW AND CONCENTRATION
155      C
156      WRITE(5,59)
157      READ(8,50) (FINIT(I),I=1,49)
158      WRITE(5,61)
159      READ(8,50) (BINIT(I),I=1,49)
160      C
161      C      READ INITIAL VALUE OF PCV
162      C
163      WRITE(5,62)
164      62      FORMAT(/// GIVE A STARTING VALUE FOR TANK VOLUME (%)'//)
165      READ(8,50) PCV(1)
166      C
167      C      EXPAND 49 FLOW VALUES
168      C
169      CALL EXPAND(FINIT,FIN,NUMS)
170      C
171      C      NORMALISE THE EXPANDED FLOW DATA

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```

172      C
173      FSUM=0.0
174      DO 110 I=1,STOP
175      110  FSUM=FSUM+FIN(I)
176      FBAR=FSUM/FLOAT(STOP)
177      DO 120 I=1,LAST
178      120  FIN(I)=FIN(I)/FBAR
179      C
180      C   EXPAND 49 CONCENTRATION VALUES
181      C
182      CALL EXPAND(BINIT,BIN,NUMS)
183      BOUT(LAST)=BIN(1)
184      C
185      C   STORE NORMALISED INFLUENT FLOW AND LOAD
186      C   VALUES IN TEMPORARY FILES FOR PLOTTING
187      C
188      LSUM=0.0
189      DO 70 I=1,STOP
190      LIN(I)=FIN(I)*BIN(I)
191      70  LSUM=LSUM+LIN(I)
192      LIN(LAST)=LIN(1)
193      LBAR=LSUM/FLOAT(STOP)
194      DO 90 I=1,LAST
195      90  LIN(I)=LIN(I)/LBAR
196      WRITE(22,63) (FIN(I),I=1,LAST)
197      WRITE(23,63) (LIN(I),I=1,LAST)
198      63  FORMAT(6(1X,F9.3))
199      C
200      C   CALCULATE DIVISION OF FLOWS
201      C
202      DO 10 I=1,LAST
203      C
204      C   FLOW SPLITTING
205      C
206      IF(ITYPE.EQ.1) THEN
207          FINSTR(I)=GAMMA*FIN(I)
208          FINTNK(I)=(1.0-GAMMA)*FIN(I)
209      C
210      C   FLOW TOPPING
211      C
212      ELSE IF(ITYPE.EQ.2) THEN
213          FINSTR(I)=GAMMA @ FBAR=1.00
214          IF(FINSTR(I).GT.FIN(I)) FINSTR(I)=FIN(I)
215          FINTNK(I)=FIN(I)-FINSTR(I)
216          END IF
217      10  CONTINUE
218      C
219      C   CALCULATE FRACTIONAL DIVISION OF FLOWS
220      C
221      TNKSUM=0.0
222      STRSUM=0.0
223      DO 20 I=1,STOP
224      STRSUM=STRSUM+FINSTR(I)
225      20  TNKSUM=TNKSUM+FINTNK(I)
226      SUM=STRSUM+TNKSUM
227      FRASTR=STRSUM/SUM
228      FRATNK=TNKSUM/SUM

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229      WRITE(5,60) FRASTR,FRATNK
230      60  FORMAT(///5X,'FRACTIONAL FLOW APPORTIONMENT',
231      1/,8X,'DIRECT TO PROCESS = ',F5.3,
232      2/,8X,'VIA EQUAL. TANK   = ',F5.3///)
233      C
234      C   AVERAGE TANK OUTFLOW EQUALS FRATNK (FBAR=1.0)
235      C
236      DO 30 I=1, LAST
237      30  FOUT(I)=FRATNK
238      C
239      C   OPTIMIZE TANK PROFILE FOR
240      C   MIXED EXIT STREAM
241      C
242      C
243      C   LOOP TO INITIALISE PCV & FOUT TEMPORARY ARRAYS
244      C
245      DO 130 I=1, LAST
246      FOUTT(I)=FOUT(I)
247      130  PCVT(I)=PCV(I)
248      KOUNT=0
249      KTPRT=0
250      GO TO 240
251      250  DO 260 JCYC=1, NCYC
252      KTPRT=KTPRT+1
253      NUM=1-DELT
254      E(1)=E(FINAL)
255      C
256      C   LOOP TO CARRY OUT ONE PROFILE IMPROVEMENT
257      C
258      DO 140 I=1, ITER
259      NUM=NUM+DELT
260      IOPT=0
261      J=I+1
262      C
263      C   TRY A CHANGE IN THE PREVIOUS BEST DIRECTION
264      C
265      CHANGE=LIMIT*SIGN(I)
266      CALL NEWPCV(FINTNK,FOUTT,PCVT,NUMS,NUMC,DELT,THT,I,
267      +CHANGE, LAST, IOPT)
268      C
269      C   CHECK FOR NEGATIVE FOUTT VALUES
270      C
271      NEG=0
272      DO 150 K=1, LAST
273      IF(FOUTT(K).LT.0.0) NEG=-1
274      150  CONTINUE
275      IF(NEG.EQ.-1) THEN
276      E(J)=1.0E20
277      ELSE
278      CALL ERCALC(FINTNK,FOUTT,BIN,BOUT,BEXIT,LOUT,PCVT,NUMS,THT,
279      + FBAR,LBAR,E(J),STOP,ALPHA,BETA,ZETA,TOPLIM,BOTLIM,
280      + PCVMAX,FEXIT,FINSTR,EFLOW,ELOAD,ELIM,EDIF,METHOD)
281      END IF
282      IF(METHOD.EQ.1) THEN
283      IF(E(J).LT.E(I)) GO TO 100
284      C
285      C   LOOP TO RE-INITIALISE TEMPORARY ARRAYS

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286      C
287          DO 160 K=1, LAST
288              FOUTT(K)=FOUT(K)
289      160      PCVT(K)=PCV(K)
290      ELSE IF (METHOD.EQ.2) THEN
291      C
292      C      LOOP TO RE-INITIALISE TEMPORARY ARRAYS
293      C
294          DO 170 K=1, LAST
295              FOUTT(K)=FOUT(K)
296      170      PCVT(K)=PCV(K)
297              IF (E(J).LT.E(I)) GO TO 100
298      END IF
299      C
300      C      TRY A CHANGE IN THE OPPOSITE DIRECTION
301      C
302          SIGN(I)=-SIGN(I)
303          CHANGE=LIMIT*SIGN(I)
304          CALL NEWPCV(FINTNK, FOUTT, PCVT, NUMS, NUMC, DELT, THT, I,
305      +CHANGE, LAST, IOPT)
306      C
307      C      CHECK FOR NEGATIVE FOUTT VALUES
308      C
309          NEG=0
310          DO 180 K=1, LAST
311              IF (FOUTT(K).LT.0.0) NEG=-1
312      180      CONTINUE
313              IF (NEG.EQ.-1) THEN
314                  E(J)=1.0E20
315              ELSE
316                  CALL ERCALC(FINTNK, FOUTT, BIN, BOUT, BEXIT, LOUT, PCVT, NUMS, THT,
317      + FBAR, LBAR, E(J), STOP, ALPHA, BETA, ZETA, TOPLIM, BOTLIM,
318      + PCVMAX, FEXIT, FINSTR, EFLOW, ELOAD, ELIM, EDIF, METHOD)
319              END IF
320              IF (METHOD.EQ.1) THEN
321                  IF (E(J).LT.E(I)) GO TO 100
322      C
323      C      LOOP TO RE-INITIALISE TEMPORARY ARRAYS
324      C
325          DO 190 K=1, LAST
326              FOUTT(K)=FOUT(K)
327      190      PCVT(K)=PCV(K)
328      ELSE IF (METHOD.EQ.2) THEN
329      C
330      C      LOOP TO RE-INITIALISE TEMPORARY ARRAYS
331      C
332          DO 200 K=1, LAST
333              FOUTT(K)=FOUT(K)
334      200      PCVT(K)=PCV(K)
335              IF (E(J).LT.E(I)) GO TO 100
336      END IF
337      C
338      C      TRY NO CHANGE
339      C
340          E(J)=E(I)
341          GO TO 140
342      100      IF (METHOD.EQ.1) THEN

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343      C
344      C      RE-SET PCV AND FOUT TO IMPROVED VALUE IF NECESSARY
345      C
346          DO 210 K=1, LAST
347          FOUT(K)=FOUTT(K)
348      210      PCV(K)=PCVT(K)
349      ELSE IF (METHOD.EQ.2) THEN
350      C
351      C      REMEMBER INTERVAL AND SIGN FOR THE BEST IMPROVEMENT
352      C
353          ISITE=I
354          ISIGN=SIGN(I)
355      END IF
356      140      CONTINUE
357          IF (METHOD.EQ.1) GO TO 80
358          IF (E(FINAL).EQ.E(1)) GO TO 80
359      C
360      C      CALCULATE PROFILE AND ERROR FOR BEST IMPROVEMENT
361      C
362          CHANGE=LIMIT*ISIGN
363          IOPT=1
364          CALL NEWPCV(FINTNK, FOUTT, PCVT, NUMS, NUMC, DELT, THT, ISITE,
365      +CHANGE, LAST, IOPT)
366          CALL ERCALC(FINTNK, FOUTT, BIN, BOUT, BEXIT, LOUT, PCVT, NUMS, THT,
367      +FBAR, LBAR, E(FINAL), STOP, ALPHA, BETA, ZETA, TOPLIM, BOTLIM,
368      +PCVMAX, FEXIT, FINSTR, EFLOW, ELOAD, ELIM, EDIF, METHOD)
369          IOPT=0
370      C
371      C      RESET PCV AND FOUT TO THE IMPROVED VALUES
372      C
373          DO 220 K=1, LAST
374          FOUT(K)=FOUTT(K)
375      220      PCV(K)=PCVT(K)
376      C
377      C      OUTPUT SOME RESULTS EACH KPRT ITERATION
378      C
379      80      KOUNT=KOUNT+1
380          ERDIF=E(FINAL)-E(1)
381          IF (KTPRT.LT.NOPRT.AND.ERDIF.NE.0.0) GO TO 230
382          WRITE(5,64)
383      64      FORMAT(/' TWO-HOURLY PCV VALUES')
384          WRITE(5,67) (PCV(JJK), JJK=1, LAST, NUMS*2)
385          WRITE(5,66) PCVMAX
386          WRITE(5,65) E(FINAL), ERDIF
387          WRITE(5,68) FBAR, LBAR
388      65      FORMAT(' E(FINAL) =', E12.6, 5X, ' DELTA ERROR =', E12.6)
389      66      FORMAT(' PCVMAX = ', F6.2)
390      68      FORMAT(' FBAR =', E12.6, 5X, ' LBAR =', E12.6/)
391      67      FORMAT(6(1X, F5.1))
392          WRITE(5,69) KOUNT, ISITE
393      69      FORMAT(' NO. OF ITERATIONS = ', I3/
394      1' LAST ADJUSTMENT AT INTERVAL', I3/)
395          EFLOD=EFLOW+ELOAD
396          WRITE(5,71) EFLOW, EFLOD, ELOAD, ELIM, EDIF
397      71      FORMAT(' AVERAGE ERROR DISTRIBUTION', /,
398      15X, 'FLOW          = ', E12.6, 8X, 'FLOW+LOAD ERROR =', E12.6, /,
399      15X, 'LOAD          = ', E12.6, /,

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400      25X,'MIN/MAX PENALTY = ',E12.6,/,
401      35X,'DF/DT PENALTY   = ',E12.6,/)
402      KTFRT=0
403      230  IF(ERDIF.EQ.0.0) GO TO 240
404      260  CONTINUE
405      240  WRITE(5,72)
406      72   FORMAT(/// 'WHAT METHOD OF OPTIMIZATION DO YOU WANT?',/,
407      16X,'STEEPEST DESCENT/FAST CONVERGENCE (SD/FC)')
408      READ(8,73) REDO
409      73   FORMAT(9A1)
410      IF(RED0(1).EQ.'F') THEN
411          METHOD=1
412      ELSE IF(RED0(1).EQ.'S') THEN
413          METHOD=2
414      END IF
415      WRITE(5,74)
416      74   FORMAT('/' 'HOW MANY ITERATIONS? WHAT LIMIT FOR FLOW ADJUSTMENT?')
417      READ(8,50) NCYC,LIMIT
418      IF(NCYC.GT.0) GO TO 250
419      C
420      C   WRITE RESULTS TO TEMPORARY FILE
421      C
422      75   FORMAT(6F9.3)
423      WRITE(20,75) (FEXIT(I),I=1,LAST)
424      WRITE(21,75) (BEXIT(I),I=1,LAST)
425      WRITE(16,75) (LOUT(I),I=1,LAST)
426      WRITE(17,75) (PCV(I),I=1,LAST)
427      WRITE(18,75) (FOUT(I),I=1,LAST)
428      WRITE(24,75) (FINSTR(I),I=1,LAST)
429      WRITE(15,75) (FINTNK(I),I=1,LAST)
430      WRITE(19,75) (BOUT(I),I=1,LAST)
431      WRITE(5,76)
432      76   FORMAT(' END OF EXECUTION')
433      CALL EXIT
434      END
435      C*****
436      C
437      C   SUBROUTINE NEWPCV
438      C   -----
439      C
440      C   THIS SUBROUTINE:
441      C       (1) CHANGES THE TANK FLOW AND VOLUME PROFILE
442      C           OVER THE JTH IMPROVEMENT INTERVAL; AND
443      C       (2) ADJUSTS THE FLOWS AND VOLUMES AT THE
444      C           REMAINING CALCULATION POINTS IN ORDER TO
445      C           MAINTAIN A MATERIAL BALANCE.
446      C
447      C   VARIABLE LIST
448      C
449      C   SEE MAIN PROGRAM
450      C   AMULT = FACTOR TO CONVERT FLOW CHANGE TO VOLUME CHANGE
451      C   CHANGE = POSSIBLE CHANGE IN FOUT AT END OF JTH INTERVAL
452      C   DELF  = CHANGE IN FOUT PER SIMULATION INTERVAL
453      C   FDEL  = ACTUAL CHANGE IN FOUT AT END OF JTH INTERVAL
454      C   FFIN  = POSSIBLE VALUE OF FOUT AT END OF JTH INTERVAL
455      C   J     = INDEX OF IMPROVEMENT INTERVAL
456      C   NSTART = SECOND POINT OF (J+1)TH IMPROVEMENT INTERVAL

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457 C      NSTOP = LAST POINT OF (J+1)TH IMPROVEMENT INTERVAL      C
458 C      START = SECOND POINT OF JTH IMPROVEMENT INTERVAL      C
459 C      STOP = LAST POINT OF JTH IMPROVEMENT INTERVAL      C
460 C      START1 = SECOND POINT OF (J+1)TH IMPROVEMENT INTERVAL      C
461 C      C
462 C*****
463 C      SUBROUTINE NEWPCV(FIN,FOUT,PCV,NUMS,NUMC,DELT,THT,J,
464 C      +CHANGE,LAST,IOPT)
465 C      INTEGER START,STOP,START1,DELT
466 C      DIMENSION PCV(1),FIN(1),FOUT(1)
467 C
468 C      IS THIS THE INTERVAL FOR OPTIMUM CHANGE?
469 C
470 C      IF(IOPT.EQ.1) THEN
471 C          START=(J-1)*DELT+2
472 C          STOP=START+DELT-1
473 C          START1=STOP+1
474 C          GO TO 60
475 C      ELSE
476 C
477 C      HAS THIS INTERVAL JUST BEEN CHANGED?
478 C
479 C          IF(J.EQ.K) GO TO 60
480 C      END IF
481 C
482 C      IF(J.NE.1) GO TO 50
483 C
484 C      DEAL WITH THE FIRST ADJUSTMENT INTERVAL OF DAY
485 C
486 C      AMULT=FLOAT(NUMS)*THT/100.
487 C      INTVLS=24*NUMS-DELT
488 C      START=2
489 C      STOP=START+DELT-1
490 C      START1=STOP+1
491 C      GO TO 60
492 C
493 C      DEAL WITH THE OTHER ADJUSTMENT INTERVALS
494 C
495 C      50 START=START1
496 C          STOP=START+DELT-1
497 C          START1=STOP+1
498 C
499 C      RECORD WHICH INTERVAL IS BEING CHANGED
500 C
501 C      60 K=J
502 C
503 C      CHANGE FLOWS AND VOLUMES OVER FIRST ADJUSTMENT INTERVAL
504 C
505 C      FFIN=FOUT(STOP)+CHANGE
506 C      FDEL=CHANGE
507 C      IF(FFIN.LE.0.0) FDEL=0.0
508 C      DELF=FDEL*FLOAT(NUMC)/FLOAT(NUMS)
509 C      KK=0
510 C      DO 10 I=START,STOP
511 C          KK=KK+1
512 C          FLO=(FIN(I)+FIN(I-1))/2.0
513 C          FOUT(I)=FOUT(I)+FLOAT(KK)*DELF

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514      DELPCV=(FLO-FOUT(I))/AMULT
515      PCV(I)=PCV(I-1)+DELPV
516 10    CONTINUE
517 C
518 C      ALTER THE NEXT ADJUSTMENT INTERVAL
519 C
520      NSTART=START1
521      IF(STOP.EQ.LAST) NSTART=2
522      NSTOP=NSTART+DELT-1
523      KK=DELT
524      DO 20 I=NSTART,NSTOP
525      KK=KK-1
526      FLO=(FIN(I)+FIN(I-1))/2.0
527      FOUT(I)=FOUT(I)+FLOAT(KK)*DELF
528      DELPCV=(FLO-FOUT(I))/AMULT
529      PCV(I)=PCV(I-1)+DELPV
530 20    CONTINUE
531 C
532 C      ALTER THE SUCCEEDING POINTS TO END OF DAY
533 C
534      KK=0
535      NSTART1=NSTART+DELT
536      IF(NSTOP.EQ.LAST) NSTART1=2
537      LENGTH=INTVLS-DELT
538      LHALF=LENGTH/2
539      HT=FDEL/(FLOAT(LHALF)/FLOAT(DELT))
540      DO 40 I=NSTART1, LAST
541      KK=KK+1
542      IF(KK.GT.LENGTH) KK=LENGTH
543      IF(KK.LE.LHALF) ADJUST=(FLOAT(KK)/FLOAT(LHALF))*HT
544      IF(KK.GT.LHALF) ADJUST=((FLOAT(LENGTH)-FLOAT(KK))/FLOAT(LHALF))*HT
545      FOUT(I)=FOUT(I)-ADJUST
546      FLO=(FIN(I)+FIN(I-1))/2.0
547      DELPCV=(FLO-FOUT(I))/AMULT
548      PCV(I)=PCV(I-1)+DELPV
549 40    CONTINUE
550 C
551      PCV(1)=PCV(LAST)
552      FOUT(1)=FOUT(LAST)
553      IEND=START-1
554      IF(IEND.LT.2.OR.IEND.GT.LENGTH) GO TO 70
555      IBEG=2
556 C
557 C      LOOP TO MAKE ADJUSTMENTS FROM 0 HOUR
558 C
559      DO 30 I=IBEG, IEND
560      KK=KK+1
561      IF(KK.LE.LHALF) ADJUST=(FLOAT(KK)/FLOAT(LHALF))*HT
562      IF(KK.GT.LHALF) ADJUST=((FLOAT(LENGTH)-FLOAT(KK))/FLOAT(LHALF))*HT
563      FOUT(I)=FOUT(I)-ADJUST
564      FLO=(FIN(I)+FIN(I-1))/2.0
565      DELPCV=(FLO-FOUT(I))/AMULT
566      PCV(I)=PCV(I-1)+DELPV
567 30    CONTINUE
568 C
569 70    RETURN
570 END

```

```

571 C*****
572 C
573 C   SUBROUTINE ERCALC
574 C   -----
575 C
576 C   THIS SUBROUTINE:
577 C       (1) CALCULATES THE TANK EXIT CONCENTRATION,
578 C           ASSUMING CSTR BEHAVIOUR;
579 C       (2) CALCULATES THE CONCENTRATION, FLOW AND LOAD
580 C           IN THE MIXED EXIT STREAM; AND
581 C       (3) CALCULATES THE ERROR ACCORDING TO THE
582 C           SPECIFIED ERROR CRITERION.
583 C
584 C
585 C   VARIABLE LIST
586 C
587 C   SEE MAIN PROGRAM
588 C
589 C*****
590 C   SUBROUTINE ERCALC(FIN,FOUT,BIN,BOUT,BEXIT,LOUT,PCV,NUMS,THT,
591 C   +FBAR,LBAR,ERROR,STOP,ALPHA,BETA,ZETA,TOPLIM,BOTLIM,
592 C   +PCVMAX,FEXIT,FINSTR,EFLOW,ELOAD,ELIM,EDIF,METHOD)
593 C   PARAMETER N=300
594 C   INTEGER STOP
595 C   REAL LOUT,LBAR,LSUM
596 C   DIMENSION FIN(1),FOUT(1),BIN(1),LOUT(1),PCV(1),BOUT(1)
597 C   DIMENSION BEXIT(1),FEXIT(1),FINSTR(1)
598 C   FSUM=0.0
599 C   LSUM=0.0
600 C   PCVMAX=0.0
601 C
602 C   CALCULATE TANK OUTLET CONCENTRATION
603 C   START CONVERGENCE CALCULATION WITH BOUT(1)=BIN(1)
604 C
605 C   BOUT(1)=BOUT(STOP+1)
606 C
607 C   DO 10 I=1,STOP
608 C       B1=(BIN(I)+BIN(I+1))/2.
609 C       P1=(PCV(I)+PCV(I+1))/2.
610 C       F1=(FIN(I)+FIN(I+1))/2.
611 C       IF(P1.GT.1.0) GO TO 40
612 C       BOUT(I+1)=BIN(I+1)
613 C       GO TO 10
614 C   40 BOUT(I+1)=BOUT(I)+F1*100.0*(B1-BOUT(I))/(P1*THT*NUMS)
615 C   10 CONTINUE
616 C
617 C   MIXING OF STREAMS
618 C
619 C   DO 20 I=1,STOP
620 C       FLOSTR=(FINSTR(I)+FINSTR(I+1))/2.0
621 C       BINSTR=(BIN(I)+BIN(I+1))/2.0
622 C       FEXIT(I+1)=FLOSTR+FOUT(I+1)
623 C       LOUT(I+1)=(FOUT(I+1)*BOUT(I)+FLOSTR*BINSTR)
624 C       BEXIT(I+1)=LOUT(I+1)/FEXIT(I+1)
625 C       FSUM=FSUM+FEXIT(I+1)
626 C       LSUM=LSUM+LOUT(I+1)
627 C   20 CONTINUE

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628      FEXIT(1)=FEXIT(STOP+1)
629      LOUT(1)=LOUT(STOP+1)
630      LBAR=LSUM/FLOAT(STOP)
631      FBAR=FSUM/FLOAT(STOP)
632      C
633      C      CALCULATE THE ERROR VALUE
634      C      AN ALTERNATIVE ERROR CALCULATION CAN BE USED
635      C
636      EFLOW=0.0
637      ELOAD=0.0
638      EDIF=0.0
639      ELIM=0.0
640      DO 30 I=1,STOP
641      P=FEXIT(I)/FBAR-1.0
642      Q=LOUT(I)/LBAR-1.0
643      EFLOW=EFLOW+P*P
644      ELOAD=ELOAD+Q*Q
645      EDIF=EDIF+(FOUT(I+1)-FOUT(I))*2
646      IF(PCV(I).GT.PCVMAX) PCVMAX=PCV(I)
647      IF(PCV(I).GT.(TOPLIM-5.0)) THEN
648          ELIM=ELIM+(PCV(I)-(TOPLIM-5.0))*6
649      ELSE IF(PCV(I).LT.(BOTLIM+5.0)) THEN
650          ELIM=ELIM+(PCV(I)-(BOTLIM+5.0))*6
651      END IF
652      30  CONTINUE
653      ERROR=ALPHA*EFLOW+(1.0-ALPHA)*ELOAD+BETA*ELIM+ZETA*EDIF
654      ERROR=ERROR/FLOAT(STOP)
655      EFLOW=ALPHA*EFLOW/FLOAT(STOP)
656      ELOAD=(1.0-ALPHA)*ELOAD/FLOAT(STOP)
657      ELIM=BETA*ELIM/FLOAT(STOP)
658      EDIF=ZETA*EDIF/FLOAT(STOP)
659      RETURN
660      END
661      C*****
662      C
663      C      SUBROUTINE EXPAND
664      C      -----
665      C
666      C      THIS SUBROUTINE INTERPOLATES BETWEEN 49 DATA
667      C      POINTS TO PRODUCE (NUMS*24+1) POINTS
668      C
669      C      VARIABLE LIST
670      C
671      C      FI = ARRAY OF POINT VALUES TO BE EXPANDED
672      C      FO = ARRAY OF EXPANDED POINT VALUES
673      C
674      C*****
675      SUBROUTINE EXPAND(FI,FO,NUMS)
676      PARAMETER N=300
677      PARAMETER M=50
678      DIMENSION FI(M),FO(N)
679      INTEGER STOP
680      K2=1
681      DO 10 J=1,48
682      K1=K2
683      K2=K1+NUMS/2
684      DO 10 I=K1,K2
685      10  FO(I)=(FI(J)+((FI(J+1)-FI(J))*FLOAT(I-K1)/(FLOAT(NUMS)/2.)))
686      END

```

B.2 GRAPH PLOTTING PROGRAMS

Two plotting programs were written for the graphical output of the equalization results from execution of TOPDA. The first was for the case of an in-line equalization configuration, while the second was for the side-line configuration. Both programs are based on the CALCOMP plotting software. Listings of the programs together with the required data input and instructions on how to execute the programs is supplied for the benefit of users who may have access to the same software.

B.2.1 In-line Equalization Configuration Plotting Program

This program, called NEWPLOT, is used to produce the graphical output of results for the case of an in-line equalization configuration. An example of the output is shown in Fig. 4.1, Chapter 4. The program consists of a main program and a number of subroutines, and is based on the CALCOMP plotting software.

A description of the data input and execution of the program is now given. Before the first execution the program must be compiled and mapped as follows:

```
@ FTN  EQUAL.NEWPLOT
@ FTN  EQUAL.NAXIS
@ FTN  EQUAL.NLINE
@ FTN  EQUAL.PAGSIZ
@ FTN  EQUAL.BRLINE
@ FTN  EQUAL.SCRIBE
@ EOF

@ MAP  EQUAL.NEWPLOT,NEWPLOT
@ EOF
```

The element EQUAL.NEWPLOT contains the following:

```
IN  EQUAL.NEWPLOT
IN  EQUAL.BRLINE,. NLINE,. NAXIS,. PAGSIZ,. SCRIBE
LIB SYS$*FTNLIB$
LIB CALCOMP*SUBR.
```

It is assumed that, on execution of TOPDA certain output has been transferred from temporary files to program elements. A list of the results which are transferred and the names of the program elements is given in Table B.2, below.

Table B.2 Data from Execution of TOPDA required as input for NEWPLOT

Temporary File No.	Element name
22.	EQUAL.FINDATA
20.	EQUAL.FEXIT
23.	EQUAL.LINDATA
16.	EQUAL.LEXIT
17.	EQUAL.PCV

Each of these elements contains $(NUMS*24 + 1)$ data values (289 values when NUMS is 12). The range of the plot (0.0 to 24.0) must be divided into the same number of data values in order to supply the corresponding abscissa values. It is assumed that the user has prepared a program element, EQUAL.TIME, containing $(NUMS*24 + 1)$ values with the first value equal to 0.0 and the last value equal to 24.0.

The program is executed as follows:

```
@ XQT,F  EQUAL.NEWPLOTCH
@ ADD  EQUAL.RUNNEWPLOT
```

In addition to listings of EQUAL.NEWPLOT and the other subroutines in Section B.2.2, a listing of the data input element EQUAL.RUNNEWPLOT is also given. In the listing of EQUAL.RUNNEWPLOT the user's attention is drawn to information peculiar to each execution which must be supplied by the user.

B.2.2 Listing of the Program Elements Required for the in-line
Equalization Configuration Plotting Program

EQUAL.NEWPLOT

EQUAL.NLINE

EQUAL.NAXIS

EQUAL.BRLINE

EQUAL.SCRIBE

EQUAL.RUNNEWPLOT

CMASP*EQUAL(1).NEWPLOT

```

1      C..  PLOTTING PROGRAM FOR IN-LINE EQUALIZATION
2      C
3          PARAMETER NDIM=300
4          INTEGER YTITLE(10),XTITLE(10)
5          REAL LBAR,LSUM
6          DIMENSION FLABEL(20)
7      C      USE X1,X2,X3 IF REQUIRED
8          DIMENSION XVALS(NDIM),Y1VALS(NDIM),Y2VALS(NDIM),Y3VALS(NDIM),
9          1Y4VALS(NDIM),Y5VALS(NDIM),SEGL1(2),SEGL2(4)
10         DATA SEGL1/0.3,0.2/
11         DATA SEGL2/0.3,0.2,0.05,0.2/
12      C..
13      10  FORMAT( )
14      505  FORMAT(20A4)
15      506  FORMAT(10A4,10A4)
16      C
17          NCR=8
18          NPR=5
19      C
20          WRITE(NPR,510)
21      510  FORMAT(' ENTER LENGTHS OF X AND Y SCALES, AND'
22          1' SCALEDATA FOR X, THEN FOR Y.',
23          2' (SCALDATA IN FORM: FIRST VALUE, UNITS/CM)',
24          3' ENTER SCALING FACTOR')
25          READ(NCR,10)XLONG,YHIGH,SCALX1,SCALX2,SCALY1,SCALY2,FCTR
26      C
27      C..  START PLOT
28          CALL PLOTS(0,0,0)
29          CALL NEWPEN(1)
30          CALL OPMS(24,'PLEASE LOAD P1-BK/I4  ')
31          CALL PAGESIZ(27.,19.)
32          CALL FACTOR(FCTR)
33      C
34      C..  READ THE TITLE CARD
35      C      WRITE(NPR,520)
36      520  FORMAT(' ENTER TITLE CARD')
37      C      READ(NCR,506)YTITLE,XTITLE
38      C
39      C..  READ THE NUMBER OF LINES PER GRAPH
40          WRITE(NPR,530)
41      530  FORMAT(' ENTER NO OF DATA SETS TO BE PLOTTED')
42          READ(NCR,10) KLines
43          WRITE(NPR,540)KLines
44      540  FORMAT(' ENTER THE',I2,' DATA SETS AFTER THE X VALUES'
45          1' LABEL')
46          2' NO. OF DATA POINTS')
47          3' @ADD ELT WITH DATA')
48      C
49      C..  READ THE X DATA
50      C..  FOR EACH DATA SET, READ 1 LABEL CARD,
51          READ(NCR,505) FLABEL
52          WRITE(NPR,505) FLABEL
53      C..  READ NUMBER OF DATA POINTS
54          READ(NCR,10) ND
55      C      NDP2=ND+2
56      C..  NB - FIRSTV & DELTAV(UNITS/CM) IN LAST TWO POSITIONS,

```

```

57      C      ELSE READ ONLY NO DATA POINTS, NOT ND+2
58      READ(NCR,10) (XVALS(I),I=1,ND)
59      C
60      C      READ THE Y DATA
61      READ(NCR,505) FLABEL
62      WRITE(NPR,505) FLABEL
63      READ(NCR,10) ND1
64      C      ND1P2=ND1+2
65      READ(NCR,10) (Y1VALS(I),I=1,ND1)
66      C..
67      C..
68      IF(KLINES.EQ.1)GO TO 30
69      C.
70      READ(NCR,505) FLABEL
71      WRITE(NPR,505) FLABEL
72      READ(NCR,10) ND2
73      C      ND2P2=ND2+2
74      READ(NCR,10)(Y2VALS(I),I=1,ND2)
75      LSUM=0.0
76      DO 40 J=2,ND2
77      40      LSUM=LSUM+Y2VALS(J)
78      LBAR=LSUM/(FLOAT(ND2)-1.
79      DO 50 J=1,ND2
80      50      Y2VALS(J)=Y2VALS(J)/LBAR
81      C..
82      IF(KLINES.EQ.2)GO TO 30
83      C.
84      READ(NCR,505) FLABEL
85      WRITE(NPR,505) FLABEL
86      READ(NCR,10) ND3
87      C      ND3P2=ND3+2
88      READ(NCR,10)(Y3VALS(I),I=1,ND3)
89      DO 20 I=1,ND3
90      20      Y3VALS(I)=Y3VALS(I)/100.0
91      C..
92      IF(KLINES.EQ.3)GO TO 30
93      C.
94      READ(NCR,505) FLABEL
95      WRITE(NPR,505) FLABEL
96      READ(NCR,10) ND4
97      C      ND4P2=ND4+2
98      READ(NCR,10)(Y4VALS(I),I=1,ND4)
99      C..
100     IF(KLINES.EQ.4)GO TO 30
101     C.
102     READ(NCR,505) FLABEL
103     WRITE(NPR,505) FLABEL
104     READ(NCR,10) ND5
105     C      ND5P2=ND5+2
106     READ(NCR,10)(Y5VALS(I),I=1,ND5)
107     C..    INSERT OTHERS IF REQUIRED
108     C
109     30     CONTINUE
110     C..    SIZE THE VALUES
111     XVALS(ND+1)=SCALX1
112     XVALS(ND+2)=SCALX2
113     Y1VALS(ND1+1)=SCALY1

```



```

114      Y1VALS(ND1+2)=SCALY2
115      DO 310 N=1,2
116      Y2VALS(ND2+N)=Y1VALS(ND1+N)
117      C      X2VALS(ND+N)=X1VALS(ND1+N)
118      Y3VALS(ND3+N)=Y1VALS(ND1+N)
119      Y4VALS(ND4+N)=Y1VALS(ND1+N)
120      310    Y5VALS(ND5+N)=Y1VALS(ND1+N)
121      C
122      C..    SET ORIGIN
123      XORIG=7.0
124      YORIG=4.0
125      CALL PLOT (XORIG,YORIG,-3)
126      WRITE(NPR,550)
127      550    FORMAT(' PLOT STARTED')
128      C..
129      C..    DRAW INNER FRAME
130      C      CALL PLOT(0.0,YHIGH+0.0,3)
131      C      CALL PLOT(XLONG+0.0,YHIGH+0.0,2)
132      C      CALL PLOT(XLONG+0.0,0.0,2)
133      C      CALL PLOT(0.0,0.0,3)
134      C..    DRAW THE AXIS
135      C      CALL AXIS(0.,0.,XTITLE,-40,XLONG,0.,XVALS(ND+1),
136      C      1XVALS(ND+2))
137      C      CALL AXIS(2.,2.,YTITLE,40,YHIGH,90.,Y1VALS(ND+1),
138      C      1Y1VALS(ND+2))
139      C
140      C..    ALTERNATIVE:  BLANK AXIS
141      C      NAXIS(XST,YST,AXLEN,STARTING LOG OR 0 FOR LINEAR SCALE,
142      C      NO. OF LGCYCS OR TICK INTVLS,ANG,CCW(1) OR CW(-1),
143      C      TICK LENGTH,LINE SOLID(2) OR BLANK(3) )
144      C
145      CALL NAXIS(0.,0.,YHIGH,0,4.,90.,-1,.25,2)
146      CALL NAXIS(0.,YHIGH,XLONG,0,6.,0.,-1,.25,2)
147      CALL NAXIS(0.,0.,XLONG,0,6.,0.,1,.25,2)
148      CALL NAXIS(XLONG,0.,YHIGH,0,4.,90.,1,.25,2)
149      C
150      GO TO (140,130,120,110,100),KLINE$
151      100    CONTINUE
152      CALL BRLINE(XVALS,Y5VALS,ND5,SEGL2,4)
153      110    CONTINUE
154      CALL BRLINE(XVALS,Y4VALS,ND4,SEGL1,2)
155      120    CONTINUE
156      CALL NLINE(XVALS,Y3VALS,ND3,1,15,5)
157      130    CONTINUE
158      CALL NLINE(XVALS,Y2VALS,ND2,1,15,0)
159      140    CONTINUE
160      CALL NLINE(XVALS,Y1VALS,ND1,1,15,2)
161      C
162      C      WRITE THE LEGEND TABLE
163      CALL SYMBOL(3.45,11.2,0.30,8HIN  OUT,0.0,8)
164      CALL SYMBOL(1.2,10.6,0.30,11HFLOW  - - -,0.0,11)
165      CALL SYMBOL(1.2,10.0,0.30,11HLOAD  - . -,0.0,11)
166      CALL SYMBOL(1.2,9.4,0.30,6HVOL FR,0.0,6)
167      CALL SYMBOL(5.3,10.75,0.25,2,0.0,-1)
168      CALL SYMBOL(5.3,10.15,0.25,0,0.0,-1)
169      CALL SYMBOL(4.40,9.55,0.25,5,0.0,-1)
170      WRITE(NPR,560)

```

```
171      560  FORMAT(' ENTER ANNOTATIONS REQUD, 4F5.2,15A4'// OTHERWISE 999.')
172          CALL SCRIBE
173      C
174      C      CALL NEWPEN(2)
175      C      CALL RECT(-.03,-.03,YHIGH+.06,XLONG+.06,0.,3)
176      C
177      C..  SIGN OFF
178          CALL PLOT (0,0,999)
179          WRITE(NPR,570)
180      570  FORMAT(' *PLOT DONE*')
181          STOP
182          END
```

CMASP*EQUAL(1).NLINE

```

1      SUBROUTINE NLINE (XARRAY,YARRAY,NPTS,INC,LINTYP,INTEQ)
2      CALCOMP HCBS PN 741013/941013 FOR UNIVAC 1107-8 NOVEMBER 1,1972
3      COPYRIGHT 1972, CALIFORNIA COMPUTER PRODUCTS INC.
4      C..... XARRAY NAME OF ARRAY CONTAINING ABSCISSA OR X VALUES.
5      C..... YARRAY NAME OF ARRAY CONTAINING ORDINATE OR Y VALUES.
6      C..... NPTS   NUMBER OF POINTS TO BE PLOTTED.
7      C..... INC    INCREMENT OF LOCATION OF SUCCESSIVE POINTS.
8      C..... LINTYP CONTROL TYPE OF LINE---SYMBOLS, LINE, OR COMBINATION.
9      C..... INTEQ  INTEGER EQUIVALENT OF SYMBOL TO BE USED, IF ANY.
10     C  MODIFIED FOR METRIC MEASURE
11         DIMENSION XARRAY(1),YARRAY(1)
12         LMIN = NPTS*INC+1
13         LDX  = LMIN+INC
14         NL   = LMIN-INC
15         FIRSTX = XARRAY(LMIN)
16         DELTAX = XARRAY(LDX)
17         FIRSTY = YARRAY(LMIN)
18         DELTAY = YARRAY(LDX)
19         CALL WHERE (XN,YN,DF)
20         DF=AMAX1(ABS((XARRAY( 1)-FIRSTX)/DELTAX-XN),
21             1     ABS((YARRAY( 1)-FIRSTY)/DELTAY-YN) )
22         DL=AMAX1(ABS((XARRAY(NL)-FIRSTX)/DELTAX-XN),
23             1     ABS((YARRAY(NL)-FIRSTY)/DELTAY-YN) )
24         IPEN = 3
25         ICODE = -1
26         NT = IABS(LINTYP)
27         IF (LINTYP) 7,6,7
28         6 NT = 1
29         7 IF (DF-DL) 9,9,8
30         8 NF = NL
31         NA = ((NPTS-1)/NT)*NT+NT-(NPTS-1)
32         KK = -INC
33         GO TO 10
34         9 NF = 1
35         NA = NT
36         KK = INC
37         10 IF (LINTYP) 11,12,13
38         11 IPENA = 3
39         ICODEA = -1
40         LSW = 1
41         GO TO 15
42         12 NA=LDX
43         13 IPENA = 2
44         ICODEA = -2
45         LSW=0
46         15 DO 30 I =1,NPTS
47             XN = (XARRAY(NF)-FIRSTX)/DELTAX
48             YN = (YARRAY(NF)-FIRSTY)/DELTAY
49             IF (NA-NT) 20,21,22
50             20 IF (LSW) 23,22,23
51             21 CALL SYMBOL(XN,YN,0.14,INTEQ,0.0,ICODE)
52             NA = 1
53             GO TO 25
54             22 CALL PLOT (XN,YN,IPEN)
55             23 NA = NA + 1
56             25 NF = NF+KK
57             ICODE = ICODEA
58             30 IPEN = IPENA
59             RETURN
60         END

```

CHASP*EQUAL(1).NAXIS

```

1      SUBROUTINE NAXIS(XST,YST,AXLEN,LOG,ANUMBR,ANG,LR,TICK,LINE)
2      C.... ROUTINE FOR DRAWING AXIS WITHOUT ANNOTATION
3      C.... (EITHER LOG OR LINEAR)
4      C....
5      C.... COMPLIMENTS OF YOUR FRIENDLY CHEM. ENG. DEPARTMENT.
6      C.... XST,YST = STARTING POSITION
7      C.... AXLEN   = LENGTH OF AXIS TO BE PLOTTED, CM
8      C....           (AXLEN MAY BE NEGATIVE)
9      C.... LOG     = STARTING POSN FOR LOG SCALE, USUALLY 1,
10     C....           OR = 0 FOR LINEAR SCALE
11     C.... ANUMBR  = NO. OF LOG CYCLES OR NO. OF TICK INTERVALS
12     C....           ALONG AXLEN.
13     C.... ANG     = 0. OR 90. FOR HORIZ. OR VERTICAL AXIS (ONLY)
14     C.... LR      = LOCATION OF TICK MARKS RELATIVE TO AXIS LINE:
15     C....           1 FOR CCW, -1 FOR CLOCKWISE.
16     C.... TICK    = SIZE OF TICK MARK, CM
17     C.... LINE    = 2 FOR SOLID, 3 FOR BLANK AXIS LINE:
18     C....           I.E., 3 WILL GIVE TICK MARKS ONLY.
19     AXIS=0.
20     DX1=0.
21     DDY1=0.
22     DX2=0.
23     DY1=0.
24     DDY1=0.
25     DY2=0.
26     LPOSN=LOG
27     IF(AXLEN.NE.0.) GO TO 11
28     WRITE(NPR,15)
29     15  FORMAT(' WARNING - AXIS LENGTH IN NAXIS ROUTINE IS ZERO.')
30     RETURN
31     11  DELTA=AXLEN/ANUMBR
32     IF(ANG.LT.10.) GO TO 1
33     DX1=TICK
34     IF(LR.GT.0) DX1=-DX1
35     DDX1=DX1
36     GO TO 2
37     1   DY1=TICK
38     IF(LR.LT.0) DY1=-DY1
39     DDY1=DY1
40     C.... START AXIS
41     2   CALL PLOT(XST,YST,3)
42     X=XST
43     Y=YST
44     3   IF(LOG.EQ.0) GO TO 4
45     C.... SET UP LOG SCALE
46     DELTA=(ALOG10(LPOSN+1)-ALOG10(LPOSN))*AXLEN/ANUMBR
47     LPOSN=LPOSN+1
48     IF(LPOSN.EQ.10) LPOSN=1
49     DX1=DDX1
50     DY1=DDY1
51     IF(LPOSN.NE.2) GO TO 4
52     IF(TICK.GT.(.1*AXLEN)) GO TO 4
53     DX1=2*DX1
54     DY1=2*DY1
55     4   IF(ANG.LT.10.)DX2=DELTA
56     IF(ANG.GT.10.) DY2=DELTA

```

```
57      AXIS=AXIS+ABS(DELTA)
58      CALL PLOT(X+DX1,Y+DY1,2)
59      CALL PLOT(X,Y,3)
60      IF(AXIS.GT.ABS(AXLEN)) GO TO 5
61      X=X+DX2
62      Y=Y+DY2
63      CALL PLOT(X,Y,LINE)
64      GO TO 3
65  5    IF(ANG.LT.10.) X=XST+AXLEN
66      IF(ANG.GT.10.) Y=YST+AXLEN
67      CALL PLOT(X,Y,LINE)
68      RETURN
69      END
```

CMASP*EQUAL(1).BRLINE

```

1      C..  BROKEN-LINE PLOTTING SUBROUTINE
2      C..  H O BUHR  DEPT. CHEM. ENG.  U C T
3      C..  THIS SUBROUTINE PLOTS A BROKEN LINE BETWEEN THE DATA POINTS
4      C..  WHOSE COORDINATES ARE STORED IN ARRAYS X & Y RESPECTIVELY.
5      C..  NPTS = NUMBER OF DATA POINTS TO BE PLOTTED.  NOTE THAT THE
6      C..          LAST TWO POSITIONS (NPTS+1 AND +2) OF X & Y
7      C..          SHOULD CONTAIN SCALING INFORMATION .
8      C..  SEGLEN IS THE NAME OF AN ARRAY CONTAINING SPECIFICATIONS FOR
9      C..  THE REPETITIVE PATTERN OF THE BROKEN LINE, GIVEN AS
10     C..  "INCHES SOLID", "INCHES BLANK", "INCHES SOLID", ----ETC
11     C..  NSEG  IS THE NUMBER OF SEGMENTS CONTAINED IN THE SPECIFICATION
12     C..  FOR SEGLEN.
13     C..  E.G.  DATA /SEGLEN/.5,.1,.1,.1/ AND NSEG=4 WILL PLOT A
14     C..  "CENTRELINE" CONFIGURATION
15     C..
16     SUBROUTINE BRLINE(X,Y,NPTS,SEGLEN,NSEG)
17     DIMENSION X(1),Y(1),SEGLEN(1)
18     C..
19     C..  SET UP STARTING VALUES
20     X2=(X(1)-X(NPTS+1))/X(NPTS+2)
21     Y2=(Y(1)-Y(NPTS+1))/Y(NPTS+2)
22     NP=1
23     IPEN=2
24     ISWTCH=1
25     INDEX=1
26     RSEG=SEGLEN(1)
27     CALL PLOT(X2,Y2,3)
28     C..
29     C..  CALCULATE LINEAR DISTANCE BETWEEN DATA POINTS
30     40  CONTINUE
31     NP=NP+1
32     IF(NP.GT.NPTS) RETURN
33     X1=X2
34     Y1=Y2
35     X2=(X(NP)-X(NPTS+1))/X(NPTS+2)
36     Y2=(Y(NP)-Y(NPTS+1))/Y(NPTS+2)
37     DX=X2-X1
38     DY=Y2-Y1
39     HYPOT=SQRT(DX**2+DY**2)
40     RGAP=HYPOT
41     C
42     100 IF(RGAP.GE.RSEG) GO TO 150
43     C..
44     C..  PLOT TO END OF CURRENT GAP, RESET RSEG
45     CALL PLOT(X2,Y2,IPEN)
46     RSEG=RSEG-RGAP
47     GO TO 40
48     C..
49     C..  PLOT TO END OF CURRENT SEGMENT, RESET RGAP
50     150 X1=X1+DX*RSEG/HYPOT
51     Y1=Y1+DY*RSEG/HYPOT
52     CALL PLOT(X1,Y1,IPEN)
53     RGAP=RGAP-RSEG
54     C..  SWITCH PEN POSITION, SET NEXT SEGMENT
55     IPEN=IPEN+ISWTCH
56     ISWTCH=-ISWTCH
57     INDEX=INDEX+1
58     IF(INDEX.GT.NSEG)INDEX=1
59     RSEG=SEGLEN(INDEX)
60     GO TO 100
61     END

```

CMASP*EQUAL(1).SCRIBE

```
1      SUBROUTINE SCRIBE
2      C.. SUBROUTINE TO ANNOTATE A PLOT.
3      C.. COMPLIMENTS OF YOUR FRIENDLY CHEM. ENG. DEPARTMENT.
4      C.. THE ROUTINE READS DATA CARDS DESCRIBING ANNOTATION REQUIRED,
5      C.. UNTIL A VALUE OF >100. IS READ IN FIRST POSITION,E.G. X=999.
6      C.. FORMAT OF DATA IS X, Y, SIZE OF LETTERS, ANGLE, AND THE
7      C.. TEXT TO BE PLOTTED (UP TO 60 LETTERS)
8      C.. FORMAT IS 4F5.2,15A4
9      INTEGER TEXT(15)
10     10  READ(8,100) X,Y,SIZE,ANGLE,TEXT
11         IF(X.GT.100.) RETURN
12         CALL SYMBOL(X,Y,SIZE,TEXT,ANGLE,60)
13         GO TO 10
14     .100  FORMAT(4F5.2,15A4)
15     END
```

CMASP*EQUAL(1).RUNNEWPLOT

3	16.00 12.00 0.0 1.5 0.0 0.17	
4	0.90	
5	5	
6	TIME VALUES	
7	289	
8	@ADD EQUAL.TIME	
9	OUTFLOW VALUES	
10	289	
11	@ADD N.FEXIT	
12	LOAD OUT VALUES	
13	289	
14	@ADD N.LEXIT	
15	PCV VALUES	
16	289	
17	@ADD N.PCV	
18	INFLOW VALUES	
19	289	
20	@ADD EQUAL.FINDATA	
21	LOAD IN VALUES	
22	289	
23	@ADD EQUAL.LINDATA	
24	-1.0 0.0 0.30 0.0 0.0	
25	16.2 0.0 0.30 0.0 0.0	
26	-1.0 2.9 0.30 0.0 0.5	
27	16.2 2.9 0.30 0.0 0.5	
28	-1.0 5.9 0.30 0.0 1.0	
29	16.2 5.9 0.30 0.0 1.0	
30	-1.0 8.9 0.30 0.0 1.5	
31	16.2 8.9 0.30 0.0 1.5	
32	-1.0 11.7 0.30 0.0 2.0	
33	16.2 11.7 0.30 0.0 2.0	
34	0.0 -0.5 0.30 0.0 0	
35	2.5 -0.5 0.30 0.0 4	
36	5.25-0.5 0.30 0.0 8	
37	7.8 -0.5 0.30 0.0 12	
38	10.5 -0.5 0.30 0.0 16	
39	13.15-0.5 0.30 0.0 20	
40	15.4 -0.5 0.30 0.0 24	
41	5.8 -1.5 0.4 0.0 TIME (HOURS)	
42	-1.5 1.0 0.4 90.0 FLOW AND LOAD (NORMALIZED)	
43	18.0 2.0 0.4 90.0 FRACTIONAL TANK VOLUME	
44	0.6 14.2 0.35 0.0 CONFIGURATION : IN-LINE	← *
45	0.6 13.6 0.30 0.5 TANK HOLD-UP = 5.5 HOURS	← *
46	0.6 13.0 0.30 0.0 HOLD-UP LIMS. MAX = 100.0%	← *
47	0.6 12.4 0.30 0.0 MIN = 0.0%	← *
48	10.5 13.0 0.30 0.0 EQUAL. WT. FACTOR:	
49	11.0 12.4 0.30 0.0 ALPHA = 0.10	← *
50	999.	

* Data peculiar to each plot supplied by user

B.2.3 Side-line Equalization Configuration Plotting Program

An example of the graphical output of results for a side-line equalization installation is shown in Fig. 4.15, Chapter 4. The program, called SIDEPLOT, consists of a main program and a number of subroutines. These subroutines are common to the plotting program for the case of in-line equalization.

The program must initially be compiled and mapped in a similar manner:

```
@ FTN  EQUAL.SIDEPLOT
@ FTN  EQUAL.NAXIS
@ FTN  EQUAL.NLINE
@ FTN  EQUAL.PAGSIZ
@ FTN  EQUAL.BRLINE
@ FTN  EQUAL.SCRIBE
@ EOF

@ MAP  EQUAL.SIDEPLOT, . SIDEPLOT
@ EOF
```

The element EQUAL.SIDEPLOT contains the following

```
IN  EQUAL.SIDEPLOT
IN  EQUAL.BRLINE, . NLINE, . NAXIS, . PAGSIZ, . SCRIBE
LIB  SYS$*FTNLIB$
LIB  CALCOMP*SUBR.
```

The information which must be transferred from temporary files to program elements on execution of TOPDA is listed in Table B.3, below:

Table B.3 Data from Execution of TOPDA required as Input for SIDEPLOT

Temporary File No.	Element Name
22.	EQUAL.FINDATA
24.	EQUAL.FINTNK
15.	EQUAL.FINSTR
20.	EQUAL.FEXIT
18.	EQUAL.FOUT
17.	EQUAL.PCV
23.	EQUAL.LINDATA
16.	EQUAL.LEXIT

A program element EQUAL.TIME containing the corresponding abscissa values is prepared in the manner described in Section B.2.1.

The program is executed as follows:

```
@ XQT,F  EQUAL.SIDEPLOTCH
@ ADD  EQUAL.RUNSIDEPLOT
```

Listings of the main program, together with a listing of the data input element EQUAL.RUNSIDEPLOT, is given in Section B.2.4. The user's attention is drawn to input data in EQUAL.RUNSIDEPLOT which must be supplied by the user, as this information is peculiar to each execution. The subroutines which are common to the plot for in-line equalization are listed in Section B.2.2.

B.2.4 Listing of the Program Elements Required for the Side-line
Equalization Configuration Plotting Program

EQUAL.SIDEPLOT

EQUAL.RUNSIDEPLOT

CHASP*EQUAL(1).SIDEPLOT

```

1      C.  PLOTTER PROGRAM FOR SIDE-LINE EQUALIZATION.
2      C
3          PARAMETER NDIM=600
4          INTEGER YTITLE(10),XTITLE(10)
5          REAL LBAR,LSUM
6          DIMENSION FLABEL(20)
7      C  USE X1,X2,X3 IF REQUIRED
8          DIMENSION XVALS(NDIM),Y1VALS(NDIM),Y2VALS(NDIM),Y3VALS(NDIM),
9          Y4VALS(NDIM),Y5VALS(NDIM),Y6VALS(NDIM),SEGL1(2),SEGL2(4),
10         Y7VALS(NDIM),Y8VALS(NDIM)
11         DATA SEGL1/0.2,0.3/
12         DATA SEGL2/0.4,0.3,0.05,0.3/
13     C..
14     10  FORMAT( )
15     505  FORMAT(20A4)
16     506  FORMAT(10A4,10A4)
17     C
18         NCR=8
19         NPR=5
20     C
21         WRITE(NPR,510)
22     510  FORMAT(' ENTER LENGTHS OF X AND Y SCALES, AND'
23         '$/' SCALEDATA FOR X, THEN FOR Y.',
24         '$/' (SCALDATA IN FORM: FIRST VALUE, UNITS/CM)',
25         '$/' ENTER SCALING FACTOR')
26         READ(NCR,10)XLONG,YHIGH,SCALX1,SCALX2,SCALY1,SCALY2,FCTR
27     C
28     C..  START PLOT
29         CALL PLOTS(0,0,0)
30         CALL NEWPEN(1)
31         CALL OPNES(24,'PLEASE LOAD P1-BK/I4  ')
32         CALL PAGESIZ(21.,30.)
33         CALL FACTOR(FCTR)
34     C
35     C.. READ THE TITLE CARD
36     C  WRITE(NPR,520)
37     520  FORMAT(' ENTER TITLE CARD')
38     C  READ(NCR,506)YTITLE,XTITLE
39     C
40     C.. READ THE NUMBER OF LINES PER GRAPH
41         WRITE(NPR,530)
42     530  FORMAT(' ENTER NO OF DATA SETS TO BE PLOTTED')
43         READ(NCR,10) KLines
44         WRITE(NPR,540)KLines
45     540  FORMAT(' ENTER THE',I2,' DATA SETS AFTER THE X VALUES'/
46         1' LABEL'/
47         2' NO. OF DATA POINTS'/
48         3' @ADD ELT WITH DATA')
49     C
50     C.. READ THE X DATA (TIME VALUES)
51     C.. FOR EACH DATA SET, READ 1 LABEL CARD,
52         READ(NCR,505) FLABEL
53         WRITE(NPR,505) FLABEL
54     C.. READ NUMBER OF DATA POINTS
55         READ(NCR,10) ND
56     C.. NB - FIRSTV & DELTAV(UNITS/CM) IN LAST TWO POSITIONS,

```

```

115 57 C XVALS(ND+1)=0
116 58 C READ(NCR,10) (XVALS(I),I=1,ND)
117 59 C Y1VALS(ND+1)=SCALY1
118 60 C READ THE Y1 DATA (TOTAL INFLOW)
119 61 Y2 READ(NCR,505) FLABEL
120 62 Y2 WRITE(NPR,505) FLABEL
121 63 Y4 READ(NCR,10) (Y1VALS(I),I=1,ND)
122 64 C.. Y1VALS(ND+1)=Y1VALS(ND)
123 65 C Y4 READ THE Y2 DATA (FLOW TO TANK)
124 66 Y4 READ(NCR,505) FLABEL
125 67 C.. Y4 WRITE(NPR,505) FLABEL
126 68 C READ(NCR,10) (Y2VALS(I),I=1,ND)
127 69 C.. SET CAXIS IN
128 70 C X0 READ THE Y3 DATA (FLOW STRAIGHT)
129 71 Y0 READ(NCR,505) FLABEL
130 72 C.. Y0 WRITE(NPR,505) FLABEL
131 73 Y0 READ(NCR,10) (Y3VALS(I),I=1,ND)
132 74 C.. FORMATTED PLOT STARTING
133 75 C.. READ THE Y4 DATA (TOTAL OUTFLOW)
134 76 C.. Y0 READ(NCR,505) FLABEL
135 77 C.. Y0 WRITE(NPR,505) FLABEL
136 78 C.. Y4 READ(NCR,10) (Y4VALS(I),I=1,ND)
137 79 C.. CALL PLOT (LONG,0.0,0.0,3)
138 80 C.. Y4 READ THE Y5 DATA (TANK OUTFLOW)
139 81 C.. Y4 READ(NCR,505) FLABEL
140 82 C.. Y4 WRITE(NPR,505) FLABEL
141 83 C.. Y4 READ(NCR,10) (Y5VALS(I),I=1,ND)
142 84 C.. CALL AXIS (2,2, YTITLE,49, (HIGH,Y0, Y1VALS(ND+1),
143 85 C.. Y1 READ THE Y6 DATA (PERCENT VOLUME)
144 86 C.. READ(NCR,505) FLABEL
145 87 C.. Y1 WRITE(NPR,505) FLABEL
146 88 C.. Y1 READ(NCR,10) (Y6VALS(I),I=1,ND) OR 0 FOR LINEAR SCALE,
147 89 C.. 10. OF LOGS OR TICK INTERVALS, ANG, COS(1) OR SIN(1),
148 90 C.. TICK LENGTH, LINE SOLID(2) OR DASH(3)
149 91 C.. DO 20, I=1,ND
150 92 C.. Y6VALS(I)=Y6VALS(I)/50.0
151 93 C.. CALL AXIS (0, HIGH, LONG,0.6,0.0,-1,.25,2)
152 94 C.. READ THE Y7 DATA (LOAD IN)
153 95 C.. Y2 READ(NCR,505) FLABEL
154 96 C.. Y2 WRITE(NPR,505) FLABEL
155 97 C.. Y2 READ(NCR,10) (Y7VALS(I),I=1,ND)
156 98 C.. CALL AXIS (0, HIGH, LONG,0.6,0.0,-1,0.25,2)
157 99 C.. READ THE Y8 DATA (LOAD OUT)
158 100 C.. Y2 READ(NCR,505) FLABEL
159 101 C.. Y2 WRITE(NPR,505) FLABEL
160 102 C.. Y2 READ(NCR,10) (Y8VALS(I),I=1,ND)
161 103 C.. LSUM=0.0 (XVALS, Y0VALS, ND, 1,0,0)
162 104 C.. DO 40 J=2,ND,-3)
163 105 C.. LSUM=LSUM+Y8VALS(J)
164 106 C.. LBAR=LSUM/(FLOAT(ND)-1.0)
165 107 C.. DO 50 J=1,ND,-3)
166 108 C.. Y8VALS(J)=Y8VALS(J)-LBAR
167 109 C.. CALL AXIS (XVALS, Y0VALS, ND, SEGL1,2)
168 110 C.. INSERT OTHERS IF REQUIRED SEGL2,4)
169 111 C.. CALL PLOT (0,0,-3)
170 112 C.. SIZE THE VALUES Y1VALS(ND,1,0,0)
171 113 C.. XVALS(ND+1)=SCALX1

```

```
171      CALL BRLINE(XVALS,Y3VALS,ND,SEGL2,4)
172      CALL PLOT(0.,-18.,-3)
173      C
174      WRITE(NPR,560)
175      560  FORMAT(' ENTER ANNOTATIONS REQUD, 4F5.2,15A4'/' OTHERWISE 999.')
176      CALL SCRIBE
177      C
178      C      CALL NEWPEN(2)
179      C      CALL RECT(-.03,-.03,YHIGH+.06,XLONG+.06,0.,3)
180      C
181      C..  SIGN OFF
182      CALL PLOT (0,0,999)
183      WRITE(NPR,570)
184      570  FORMAT(' *PLOT DONE*')
185      STOP
186      END
```

57	-1.5	20.1	0.3	90.0	INFLOW		
58	-1.5	8.4	0.3	90.0	LOAD		
59	-1.5	0.15	0.3	90.0	FRACTIONAL TANK VOL		
60	0.0	26.2	0.35	0.0	CONFIG. : SIDE-LINE(FLOW TOPPING)	←	*
61	0.0	25.6	0.30	0.0	TANK HOLD-UP = 5.0 HOURS	←	*
62	0.0	25.0	0.30	0.0	TANK LEVELS MAX =100.0%	←	*
63	0.0	24.4	0.30	0.0	MIN = 0.0%	←	*
64	7.9	25.6	0.30	0.0	CONSTANTS:		
65	8.4	25.0	0.30	0.0	ALPHA = 0.50	←	*
66	8.4	24.4	0.30	0.0	GAMMA = 0.70	←	*
67	999.						

* Data peculiar to each run supplied by user

A P P E N D I X C

SIMULATION PROGRAMS FOR TESTING THE
EQUALIZATION CONTROL STRATEGYC.1 INTRODUCTION

Development of two different computer programs for the simulation of controlled equalization tank response has been discussed in Section 4, Chapter 5. The first of these programs (SIMCONOLD) was developed along similar lines to the equalization algorithm program, TOPDA; the program can be used to simulate the controlled response of either an in-line or a side-line equalization tank and utilizes finite difference integration (with short step lengths) for that section of the program computing the expected tank hold-up and concentration response under the expected input patterns for an ensuing 24 hour period. Certain problems were encountered in the use of this program; namely, the relatively large program storage requirement and the long computation times required for simulation of the controlled tank performance for a two-day period, the simulation period generally used in this investigation. This led to the development of a second simulation program (SIMCON). The program SIMCON is more suitable for simulations of the controlled equalization tank response because (1) the program storage requirement is fairly small as the program is less generalized than SIMCONOLD (only the in-line case is considered); and (2) execution time is reduced to about one tenth of that required for SIMCONOLD as second order Runge Kutta integration (with relatively long step lengths) is used in the equalization algorithm section of the program. In Chapters 5 and 6 results for both in-line and side-line equalization tanks are presented. For completeness, therefore, both the programs SIMCONOLD and SIMCON are listed here, together with instructions for their use. In addition the single plotting program used for presenting the results obtained from use of either simulation program is also presented.

C.2 SIMCONOLD - SIMULATION PROGRAM FOR THE CONTROLLED RESPONSE OF EITHER IN-LINE OR SIDE-LINE EQUALIZATION TANK

C.2.1 General Description

SIMCONOLD is an ASCII FORTRAN computer program which simulates the controlled response of either an in-line or a side-line equalization tank of a specified size under inputs of flow rate and concentration specified by the user. The main feature of the program is that the equalization algorithm (developed in Chapter 3 and modified slightly in Chapter 5) is used to determine the optimum tank outflow rate at specified intervals.

Details of the workings of the program are very similar to those presented for the equalization algorithm program and are not repeated here (see flowcharts in Fig. 3.4, Chapter 3). However, it is worth mentioning certain general features of the program as this will facilitate understanding of the data input discussed in the next Section:

- (a) All arithmetic is performed in single precision.
- (b) The program is not designed for interactive use as was the case for the equalization algorithm program TOPDA. Rather, it is intended that the program is used to simulate the controlled equalization tank response for some period, the length of which is determined before execution.
- (c) Details of the data input are presented at the head of the program listing. All data input is in free format.
- (d) Input flow rate and concentration data is specified as point values at 5 minute intervals. The program is structured to allow simulation of the controlled tank response for any length of time up to a two day period (i.e. 576 input pairs of flow rate and concentration); however, only small changes are required to allow simulation for longer periods.
- (e) Certain printed output of results is supplied during program execution; an example of this output is presented in the following section. In addition the data required for the graphical output of results is written to a temporary file

during execution to facilitate use of the plotting program described in Section C.4.

C.2.2 A Typical Runstream for SIMCONOLD

This Section presents an example of the input data required for execution of the program SIMCONOLD, together with an example of the printed output. It is assumed that the program contained in the element CMASP*EQUAL.SIMCONOLD has been compiled and mapped to give an executable absolute version in the element .SIMCONOLDABS.

Much of the input data is identical to that required for the equalization algorithm program TOPDA. Therefore it is only necessary to present a sample of the input data here. The reader is referred to the discussion in Section B.1.2 and to the detailed instructions regarding input data contained in the listing of the program (Section C.2.3).

The following "canned" runstream is typical of those used for producing the results presented and discussed in Chapters 5 and 6; the printed output of results is directed to a print file which may be directed to a printer (by the @SYM command) or viewed directly on a VDU.

```

1      @RUN
2      @DELETE,C PF.
3      @ASG,UP PF.,F2
4      @SYM,D PRINT$
5      @BRKPT PRINT$/PF
6      @XQT CMASP*EQUAL.SIMCONOLDABS
7      1
8      0.0
9      5.5
10     95.0 5.0
11     0.5 2.0E-06 20.0
12     12
13     6
14     0.02
15     1 1 2
16     @ADD CMASP*EQUAL.FIN1
17     @ADD CMASP*EQUAL.BIN1
18     @ADD CMASP*EQUAL.FIN2
19     @ADD CMASP*EQUAL.BIN2
20     92.0 971.0
21     @ADD CMASP*EQUAL.FLOWCONCDATA
22     -99.9 999.9
23     @COPY,I 21.,CMASP*EQUAL.PLOTDATA
24     @ED CMASP*EQUAL.PLOTDATA,.PLOTDATA
25     @BRKPT PRINT$
26     @SYM,D PRINT$
27     @FREE PF.
```

The printed results obtained from this execution of the program SIMCONOLD for simulation of the control strategy performance over 24 hours are presented overleaf. The information supplied is as follows:

- Certain information regarding the input data.
- The tank outflow rate setting for each control interval during the simulation period; this data is supplied in normalized units to simplify evaluation of the control strategy performance.
- The effluent load rate at the start of each control interval.
- The tank hold-up (as a percentage of the total tank hold-up) at the start of each control interval.
- Details of the individual components of the error expression as well as the number of cycles required to determine the optimum tank outflow rate at the start of each control interval using the equalization algorithm.

```
2: *****
3: INPUT DATA
4: *****
5:
6:
7: MEAN TANK RETENTION TIME (HOURS) = 5.5
8:
9: TANK VOLUME LIMITS (%) :
10:   MAXIMUM = 95.0
11:   MINIMUM = 5.0
12:
13: ERROR EXPRESSION WEIGHTING FACTORS :
14:   ALPHA = .50
15:   BETA = .2-005
16:   OMEGA = 20.0
17:
18: MINIMUM FLOW ADJUSTMENT = .02
19:
20: SEQUENCE OF DAY TYPES :
21:
22: WEEKDAY
23:
24: WEEKDAY
25:
26: WEEKDAY
27:
28:
29:
30:
```

	TIME (HRS.)	OUTFLOW RATE	EFF. LOAD RATE	TANK % HOLD-UP	FLOW	ERROR DISTRIBUTION		TOTAL	NO. OF ITERATIONS
						LOAD	LIMIT		
31:									
32:									
33:									
34:									
35:									
36:									
37:									
38:									
39:	.0	1.000	971.0	92.0	.0000	.0111	.0013	.0125	1
40:	.5	1.000	960.9	90.6	.0000	.0843	.0016	.0861	1
41:	1.0	1.000	951.4	89.6	.0000	.0610	.0013	.0625	1
42:	1.5	1.020	960.2	88.6	.0000	.0394	.0017	.0414	2
43:	2.0	1.020	951.0	87.3	.0000	.0256	.0016	.0277	1
44:	2.5	1.020	946.1	85.9	.0001	.0179	.0016	.0199	2
45:	3.0	1.020	956.5	84.1	.0001	.0148	.0015	.0169	1
46:	3.5	1.020	967.0	82.2	.0001	.0136	.0014	.0154	2
47:	4.0	1.020	965.0	80.2	.0001	.0130	.0015	.0149	2
48:	4.5	1.020	958.9	77.8	.0001	.0124	.0013	.0140	2
49:	5.0	1.020	949.6	74.7	.0001	.0137	.0009	.0152	1
50:	5.5	1.020	939.9	70.5	.0001	.0161	.0010	.0178	1
51:	6.0	1.020	930.6	65.6	.0001	.0207	.0009	.0222	1
52:	6.5	1.020	920.2	60.1	.0002	.0209	.0007	.0222	2
53:	7.0	1.020	908.9	54.0	.0002	.0152	.0026	.0184	1
54:	7.5	1.000	879.9	47.6	.0001	.0122	.0014	.0146	3
55:	8.0	.980	849.1	41.7	.0002	.0099	.0014	.0125	2
56:	8.5	.980	830.3	36.3	.0001	.0082	.0016	.0108	1
57:	9.0	.980	802.0	31.4	.0001	.0075	.0014	.0099	1
58:	9.5	.980	771.6	26.7	.0001	.0075	.0008	.0092	2
59:	10.0	.980	752.8	21.9	.0001	.0072	.0007	.0089	1
60:	10.5	1.000	752.2	17.0	.0001	.0068	.0007	.0085	1
61:	11.0	1.000	709.4	11.9	.0001	.0062	.0010	.0079	1
62:	11.5	.980	612.8	6.7	.0001	.0040	.0045	.0093	3
63:	12.0	.417	207.0	1.6	.0000	.0113	.1082	.1170	2

C.2.3 Listing of Program SIMCONOLD

CMASP*EQUAL(1).SIMCONOLD

```

1      C*****
2      C
3      C   PROGRAM TO SIMULATE OPERATION OF CONTROL STRATEGY
4      C   -----
5      C
6      C   THIS PROGRAM SIMULATES THE CONTROLLED RESPONSE OF EITHER
7      C   AN IN-LINE OR A SIDE-LINE EQUALIZATION TANK UNDER SPECIFIED
8      C   INPUTS OF FLOW RATE AND CONCENTRATION WHEN THE OUTFLOW RATE
9      C   FROM THE TANK IS DETERMINED THROUGH APPLICATION OF THE
10     C   EQUALIZATION ALGORITHM DEVELOPED AT THE UNIVERSITY OF CAPE
11     C   TOWN.
12     C
13     C*****
14     C   NOTE: IN THAT PART OF THE PROGRAM WHICH INVOLVES THE
15     C   EQUALIZATION ALGORITHM, FINITE DIFFERENCE
16     C   INTEGRATION IS USED TO COMPUTE THE TANK HOLD-UP
17     C   AND CONCENTRATION RESPONSE. THIS METHOD IS ALSO
18     C   USED TO COMPUTE THE RESPONSE OF THE 'REAL' TANK
19     C   UNDER THE SPECIFIED INPUTS OF FLOW RATE AND CONC.
20     C*****
21     C
22     C   DETAILS FOR DATA INPUT (ALL DATA IN FREE FORMAT)
23     C   -----
24     C
25     C   CARD 1 : ITYPE - SPECIFIES METHOD OF FLOW DIVISION IN
26     C   SIDE-LINE EQUALIZATION
27     C   =1 FOR FLOW SPLITTING
28     C   =2 FOR FLOW TOPPING
29     C   =1 OR 2 FOR IN-LINE CASE
30     C   E.G. 1
31     C
32     C   CARD 2 : GAMMA - FLOW DIVISION FACTOR FOR SIDE-LINE
33     C   EQUALIZATION
34     C   =0.0 FOR IN-LINE CASE
35     C   E.G. 0.30
36     C
37     C   CARD 3 : THT - MEAN TANK RETENTION TIME(HOURS)
38     C   E.G. 6.0
39     C
40     C   CARD 4 : TOPLIM,BOTLIM - UPPER AND LOWER ALLOWABLE TANK
41     C   HOLD-UP LIMITS(%)
42     C   E.G. 95.0 5.0
43     C
44     C   CARD 5 : ALPHA,BETA,OMEGA - ERROR EXPRESSION WEIGHTING
45     C   FACTORS
46     C   E.G. 0.5 2.0E-06 25.0
47     C
48     C   CARD 6 : NUMSIM - NO. OF SIMULATION INTERVALS PER HOUR
49     C   E.G. 12
50     C
51     C   CARD 7 : NUMCTL - NO. OF SIMULATION INTERVALS PER CONTROL
52     C   INTERVAL FOR 'REAL' TANK
53     C   E.G. 6
54     C
55     C   CARD 8 : LIMIT - SIZE OF INCREMENTAL CHANGE MADE TO
56     C   FLOW RATE BY EQUALIZATION ALGORITHM

```

```

57.      C          E.G. 0.02                                C
58      C                                                    C
59      C      CARD 9 : JTODAY,JTOMOR,JNEXT - DAY-TYPES FOR TODAY,  C
60      C          TOMORROW AND NEXT DAY                        C
61      C          =1 FOR WEEKDAY                               C
62      C          =2 FOR WEEKEND DAY                           C
63      C          E.G. 1 1 2                                   C
64      C                                                    C
65      C      CARD 10: 49 HALF-HOURLY POINT VALUES OF HISTORICAL  C
66      C          INFLOW RATE DATA FOR A WEEKDAY              C
67      C          E.G. @ADD EQUAL.FIN1                         C
68      C                                                    C
69      C      CARD 11: 49 HALF-HOURLY POINT VALUES OF HISTORICAL  C
70      C          CONCENTRATION DATA FOR A WEEKDAY            C
71      C          E.G. @ADD EQUAL.BIN1                         C
72      C                                                    C
73      C      CARD 12: 49 HALF-HOURLY POINT VALUES OF HISTORICAL  C
74      C          INFLOW RATE DATA FOR A WEEKEND              C
75      C          E.G. @ADD EQUAL.FIN2                         C
76      C                                                    C
77      C      CARD 13: 49 HALF-HOURLY POINT VALUES OF HISTORICAL  C
78      C          CONCENTRATION DATA FOR A WEEKEND            C
79      C          E.G. @ADD EQUAL.BIN2                         C
80      C                                                    C
81      C      CARD 14: PCV(1),BOUTA - INITIAL TANK HOLD-UP AND      C
82      C          CONCENTRATION AT START OF SIMULATION          C
83      C          E.G. 90.0 870.0                              C
84      C                                                    C
85      C      CARD 15: ACTUAL INFLOW RATE AND CONCENTRATION AT      C
86      C          START OF SIMULATION                           C
87      C          E.G. 41.0 865.0                              C
88      C                                                    C
89      C      CARD 16: POINT VALUES OF ACTUAL INFLOW RATE AND      C
90      C          CONCENTRATION AT INTERVALS OF '60/NR'         C
91      C          MINUTES AFTER START                           C
92      C          E.G. 41.5 876.0                              C
93      C          43.7 830.0                                    C
94      C          40.5 890.0                                    C
95      C                                                    C
96      C      CARD 17: -99.9 99.9 - STOPPING CARD                C
97      C                                                    C
98      C      UNITS : ANY UNITS FOR BOTH FLOW RATE AND CONCENTRATION C
99      C          PROVIDING THE UNITS ARE COMPATIBLE            C
100     C                                                    C
101     C*****
102     C      PARAMETER N=289
103     C      PARAMETER M=49
104     C      DIMENSION FINCTL(2,N),BINCTL(2,N),BOUTPR(N),LINCTL(2,N),
105     C      1FOUTPR(N),FTKCTL(2,N)
106     C      DIMENSION E(M),FINIT(2,M),BINIT(2,M),ISIGN(M)
107     C      DIMENSION PCV(2),FINACT(2),FTKACT(2),FSTACT(2),BINACT(2)
108     C      INTEGER FINAL
109     C      REAL LOUTA,LOUTPR,LIMIT,LINCTL,LSUM,LBAR
110     C      CALL UNDSCT(3)
111     C      CALL DIVSET(3)
112     C      CALL OVSET(3)
113     C      CALL OVUNFL(3)
114     C

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115      50      FORMAT( )
116      150      FORMAT(3X,F4.1,4X,F5.3,4X,F6.1,6X,F4.1,8X,5(F6.4,2X),9X,I2)
117      250      FORMAT(5(F9.3))
118      350      FORMAT(////5X,20('*')/6X,'SIMULATION RESULTS'/5X,20('*')
119              1//3X,'TIME    OUTFLOW EFF. LOAD    TANK %',18X,
120              2'ERROR DISTRIBUTION',18X,'NO. OF'
121              3/2X,'(HRS.)    RATE    RATE    HOLD-UP    FLOW    ',
122              4'LOAD    LIMIT DF/DT    TOTAL    ITERATIONS'
123              5/2X,6(' '),4X,4(' '),5X,4(' '),6X,7(' '),8X,4(' '),
124              64X,4(' '),3X,5(' '),3X,5(' '),3X,5(' '),7X,10(' ')//
125      450      FORMAT(1H1,4X,I2('*')/6X,'INPUT DATA'/5X,I2('*'))
126      550      FORMAT(/3X,'MEAN TANK RETENTION TIME (HOURS) = ',F3.1
127              1//3X,'TANK VOLUME LIMITS (%) :'/10X,'MAXIMUM = ',F4.1/
128              210X,'MINIMUM = ',F4.1//3X,'ERROR EXPRESSION WEIGHTING ',
129              3'FACTORS :'/10X,'ALPHA = ',F4.2/10X,'BETA = ',E7.1/10X,
130              4'OMEGA = ',F4.1//3X,'MINIMUM FLOW ADJUSTMENT = ',F4.2//
131              53X,'SEQUENCE OF DAY TYPES :')
132      650      FORMAT(/10X,'WEEKDAY')
133      750      FORMAT(/10X,'WEEKEND DAY')
134      C
135      C      READ IN DATA
136      C
137      READ(8,50) ITYPE
138      READ(8,50) GAMMA
139      READ(8,50) THT
140      READ(8,50) TOPLIM,BOTLIM
141      READ(8,50) ALPHA,BETA,OMEGA
142      READ(8,50) NUMSIM
143      READ(8,50) NUMCTL
144      READ(8,50) LIMIT
145      READ(8,50) JTODAY,JTOMOR,JNEXT
146      C
147      C      WRITE OUT INPUT DATA
148      C
149      WRITE(5,450)
150      WRITE(5,550) THT,TOPLIM,BOTLIM,ALPHA,BETA,OMEGA,LIMIT
151      IF(JTODAY.EQ.1) WRITE(5,650)
152      IF(JTODAY.EQ.2) WRITE(5,750)
153      IF(JTOMOR.EQ.1) WRITE(5,650)
154      IF(JTOMOR.EQ.2) WRITE(5,750)
155      IF(JNEXT.EQ.1) WRITE(5,650)
156      IF(JNEXT.EQ.2) WRITE(5,750)
157      C
158      C      TO INITIALIZE SOME ARRAYS
159      C
160      FINAL=24*NUMSIM/NUMCTL+1
161      DO 40 I=1,FINAL
162      ISIGN(I)=1
163      40  E(I)=1.0E06
164      LAST=NUMSIM*24+1
165      LASTM1=LAST-1
166      C
167      C      READ IN VARIABLES REQUIRED BY THE CONTROL ALGORITHM.
168      C      READ 49 HALF-HOURLY POINT VALUES OF HISTORICAL
169      C      INFLUENT FLOW AND CONCENTRATION, AND THE
170      C      EXPECTED OUTFLOW PROFILE
171      C

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172      DO 30 J=1,2
173      READ(8,50) (FINIT(J,I),I=1,49)
174      READ(8,50) (BINIT(J,I),I=1,49)
175      30  CONTINUE
176      READ(8,50) (FOUTPR(I),I=1,LAST)
177      C
178      C   CONVERT FOUTPR TO (NUMCTL/NUMSIM)-HOURLY AVERAGES
179      C
180      DO 10 I=1,(24*NUMSIM/NUMCTL)
181      TOTF=0.0
182      DO 20 J=1,NUMCTL
183      20  TOTF=TOTF+FOUTPR((I-1)*NUMCTL+J)
184      FAVG=TOTF/FLOAT(NUMCTL)
185      DO 10 J=1,NUMCTL
186      FOUTPR((I-1)*NUMCTL+J)=FAVG
187      10  CONTINUE
188      FOUTPR(LAST)=FOUTPR(1)
189      C
190      C   EXPAND 49 FLOW VALUES FOR EACH DAY TYPE
191      C
192      CALL EXPAND(FINIT,FINCTL,NUMSIM)
193      C
194      C   NORMALISE THE EXPANDED FLOW DATA
195      C
196      FSUM=0.0
197      DO 101 I=1,LASTM1
198      101  FSUM=FSUM+FINCTL(1,I)
199      FBAR=FSUM/FLOAT(LASTM1)
200      DO 121 J=1,2
201      DO 120 I=1,LAST
202      120  FINCTL(J,1)=FINCTL(J,I)/FBAR
203      121  CONTINUE
204      C
205      C   EXPAND 49 CONCENTRATION VALUES FOR EACH DAY TYPE
206      C
207      CALL EXPAND(BINIT,BINCTL,NUMSIM)
208      C
209      C   SUPPLY CONTROL ALGORITHM WITH EXPECTED
210      C   FLOW THROUGH THE TANK FOR EACH DAY TYPE
211      C
212      CALL DIVIDE(FINCTL,ITYPE,GAMMA,LAST,FTKCTL)
213      C
214      C   READ INITIAL VALUE OF PCV AND BOUT
215      C
216      READ(8,50) PCV(1),BOUTA
217      C
218      C   READ AND 'NORMALIZE' ACTUAL INFLOW
219      C   AND READ ACTUAL INFLUENT CONCENTRATION
220      C   AT START OF SIMULATION
221      C
222      READ(8,50) FINACT(1),BINACT(1)
223      FINACT(1)=FINACT(1)/FBAR
224      C
225      C   FLOW SPLITTING
226      C
227      IF(ITYPE.EQ.1) THEN
228      FSTACT(1)=GAMMA*FINACT(1)

```

```

229      FTKACT(1)=(1.0-GAMMA)*FINACT(1)
230      C
231      C   FLOW TOPPING
232      C
233      ELSE IF(ITYPE.EQ.2) THEN
234          FSTACT(1)=GAMMA      @ FBAR=1.00
235          IF(FSTACT(1).GT.FINACT(1)) FSTACT(1)=FINACT(1)
236          FTKACT(1)=FINACT(1)-FSTACT(1)
237      END IF
238      C
239      C   INITIAL SET-UP
240      C
241      JKTCTL=NUMCTL
242      ITERKT=0
243      BOUTPR(LAST)=BINCTL(1,1)
244      DELTA=1./FLOAT(NUMSIM)
245      AMULT=FLOAT(NUMSIM)*THT/100.
246      WRITE(5,350)
247      C
248      C   BEGIN ITERATION
249      C
250      1001 CONTINUE
251      JKTCTL=JKTCTL+1
252      C
253      C   CONTROL ALGORITHM SETS OUTFLOW EVERY NUMCTL INTERVALS
254      C
255      IF(JKTCTL.LT.NUMCTL) GO TO 500
256      JKTCTL=0
257      CALL CONTROL(FTKCTL,FINCTL,BINCTL,FOUTPR,PCV(1),BOUTPR,NUMCTL,
258      1NUMSIM,AMULT,LAST,ISIGN,E,ALPHA,BETA,OMEGA,
259      2TOPLIM,BOTLIM,LIMIT,FOUTC,ITIME,JTODAY,JTOMOR,JNEXT,
260      3ITYPE,GAMMA,EFLOW,ELOAD,ELIM,EDIF)
261      FOUTRQ=FOUTC
262      500 CONTINUE
263      CALL SUBCTL(PCV(1),FOUTC,AMULT,FOUTRQ)
264      FOUTA=FOUTC
265      C
266      C   REAL TANK SIMULATION
267      C
268      C
269      C   READ AND "NORMALISE" THE ACTUAL INFLOW
270      C   AND READ ACTUAL INFLUENT CONCENTRATION
271      C   FOR EACH NUMSIM INTERVAL
272      C
273      READ(8,50) FINACT(2),BINACT(2)
274      C
275      C   STOPPING CONDITION
276      C
277      IF(FINACT(2).LT.0.0) CALL EXIT
278      FINACT(2)=FINACT(2)/FBAR
279      C
280      C   OUTPUT RESULTS ON MAKING A CONTROL DECISION
281      C
282      FXACT=FSTACT(1)+FOUTA
283      LOUYA=FOUTA*BOUTA+FSTACT(1)*BINACT(1)
284      IF(JKTCTL.EQ.0) THEN
285          CTIME=FLOAT(ITIME-NUMCTL-1)/NUMSIM

```

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286      WRITE(5,150) CTIME,FXACT,LOUTA,PCV(1),EFLOW,ELOAD,
287      1 ELIM,EDIF,E(FINAL),JCYC
288      END IF
289      C
290      C   STORE RESULTS FOR PLOTTING
291      C
292      WRITE(21,250) FINACT(1),BINACT(1),PCV(1),FXACT,LOUTA
293      C
294      C   FLOW SPLITTING
295      C
296      IF(ITYPE.EQ.1) THEN
297          FSTACT(2)=GAMMA*FINACT(2)
298          FTKACT(2)=(1.0-GAMMA)*FINACT(2)
299      C
300      C   FLOW TOPPING
301      C
302      ELSE IF(ITYPE.EQ.2) THEN
303          FSTACT(2)=GAMMA      @ FBAR=1.00
304          IF(FSTACT(2).GT.FINACT(2)) FSTACT(2)=FINACT(2)
305          FTKACT(2)=FINACT(2)-FSTACT(2)
306      END IF
307      C
308      C   DETERMINE PCV(2) AND BOUTA
309      C
310      FMID=(FTKACT(1)+FTKACT(2))/2.
311      PCV(2)=PCV(1)+(FMID-FOUTA)/AMULT
312      IF(PCV(2).LT.0.5) THEN
313          PCV(2)=PCV(1)
314          BOUTA=BINACT(2)
315      ELSE
316          PMID=(PCV(1)+PCV(2))/2.
317          BMID=(BINACT(1)+BINACT(2))/2.
318          BOUTA=BOUTA+FMID*(BMID-BOUTA)/(PMID*AMULT)
319          IF(BOUTA.LT.0) BOUTA=BINACT(2)
320      END IF
321      FTKACT(1)=FTKACT(2)
322      FSTACT(1)=FSTACT(2)
323      FINACT(1)=FINACT(2)
324      BINACT(1)=BINACT(2)
325      PCV(1)=PCV(2)
326      PCV(1)=PCV(2)
327      GO TO 1001
328      END
329      C*****
330      C
331      C   SUBROUTINE EXPAND
332      C   -----
333      C
334      C   THIS SUBROUTINE INTERPOLATES BETWEEN 49 DATA
335      C   POINTS TO PRODUCE (NUMS*24+1) POINTS
336      C
337      C   VARIABLE LIST
338      C
339      C   FI = ARRAY OF POINT VALUES TO BE EXPANDED
340      C   FO = ARRAY OF EXPANDED POINT VALUES
341      C
342      C*****

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343      SUBROUTINE EXPAND(FI,FO,NUMS)
344      PARAMETER N=289
345      PARAMETER M=49
346      DIMENSION FI(2,M),FO(2,N)
347      DO 20 JK=1,2
348      K2=1
349      DO 10 J=1,48
350      K1=K2
351      K2=K1+NUMS/2
352      DO 10 I=K1,K2
353      10  FO(JK,I)=(FI(JK,J)+(FI(JK,(J+1))-FI(JK,J))*FLOAT(I-K1)/
354      1(FLOAT(NUMS)/2.))
355      20  CONTINUE
356      RETURN
357      END
358      C*****
359      C
360      C      SUBROUTINE DIVIDE
361      C      -----
362      C
363      C      THIS SUBROUTINE SUPPLIES THE CONTROLLER WITH
364      C      THE ANTICIPATED DIVISION OF FLOWS
365      C
366      C*****
367      SUBROUTINE DIVIDE(FIN,ITYPE,GAMMA,LAST,FTNK)
368      PARAMETER N=289
369      DIMENSION FIN(2,N),FTNK(2,N)
370      C
371      C      CALCULATE DIVISION OF FLOWS
372      C
373      DO 30 JK=1,2
374      DO 10 I=1,LAST
375      C
376      C      FLOW SPLITTING
377      C
378      IF(ITYPE.EQ.1) THEN
379      FTNK(JK,I)=(1.0-GAMMA)*FIN(JK,I)
380      C
381      C      FLOW TOPPING
382      C
383      ELSE IF(ITYPE.EQ.2) THEN
384      FSTR=GAMMA @ FBAR=1.00
385      IF(FSTR.GT.FIN(JK,I)) FSTR=FIN(JK,I)
386      FTNK(JK,I)=FIN(JK,I)-FSTR
387      END IF
388      10  CONTINUE
389      30  CONTINUE
390      RETURN
391      END
392      C*****
393      C
394      C      SUBROUTINE CONTRL
395      C      -----
396      C
397      C      THIS SUBROUTINE SUPPLIES THE SETTING FOR THE TANK
398      C      OUTLET RATE
399      C
400      C*****

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401      SUBROUTINE CONTRL(FTKCTL,FINCTL,BINCTL,FOUTPR,PCV,BOUTPR,
402      1NUMCTL,NUMSIM,AMULT,LAST,ISIGN,E,ALPHA,BETA,OMEGA,
403      2TOPLIM,BOTLIM,LIMIT,FOUTC,ITIME,JTODAY,JTOMOR,JNEXT,
404      3ITYPE,GAMMA,EFLOW,ELOAD,ELIM,EDIF)
405      PARAMETER N=289
406      PARAMETER M=49
407      DIMENSION FTKCTL(2,N),FINCTL(2,N),BINCTL(2,N),BOUTPR(N)
408      DIMENSION E(M),ISIGN(M)
409      DIMENSION PCVC(N),PCVCT(N),FOUTPR(N),FOUTT(N),FTKEXP(N)
410      DIMENSION FSTEXP(N),BINEXP(N)
411      REAL LIMIT
412      IF(INITL.EQ.0) THEN
413          NCYC=30
414          ITIME=1
415          FOUTC=FOUTPR(1)
416          PCVC(1)=PCV
417          DO 91 I=1,(LAST-1)
418              DELPCV=(FTKCTL(JTODAY,I)-FOUTPR(I))/AMULT
419      91      PCVC(I+1)=PCVC(I)+DELPVC
420          DO 94 I=1,LAST
421              FSTEXP(I)=FINCTL(JTODAY,I)-FTKCTL(JTODAY,I)
422              BINEXP(I)=BINCTL(JTODAY,I)
423      94      FTKEXP(I)=FTKCTL(JTODAY,I)
424              DELFCT=0.0
425              INITL=10
426      ELSE
427          NCYC=15
428          FINTOT=0.0
429          DO 11 I=(ITIME-NUMCTL),(ITIME-1)
430      11      FINTOT=FINTOT+FTKCTL(JTODAY,I)
431          FINEXP=FINTOT/FLOAT(NUMCTL)
432          IF(ITIME.EQ.LAST) THEN
433              ITIME=1
434              JTODAY=JTOMOR
435              JTOMOR=JNEXT
436          END IF
437          PCVC(ITIME)=PCV
438          FINAVG=(PCV-PCVLS)*AMULT/FLOAT(NUMCTL)+FOUTC
439          DELFCT=0.4*DELFCT+0.6*(FINAVG-FINEXP)
440          CORRN=DELFCT
441          DO 92 I=ITIME,(LAST-1)
442              IF(ITYPE.EQ.1) THEN
443                  FTKEXP(I)=FTKCTL(JTODAY,I)+CORRN
444                  FSTEXP(I)=(GAMMA/(1.-GAMMA))*FTKEXP(I)
445              ELSE IF(ITYPE.EQ.2) THEN
446                  FSTEXP(I)=GAMMA
447                  IF(FSTEXP(I).GT.FINCTL(JTODAY,I)) THEN
448                      FSTEXP(I)=FINCTL(JTODAY,I)+CORRN
449                      FTKEXP(I)=0.0
450                  ELSE
451                      FTKEXP(I)=FTKCTL(JTODAY,I)+CORRN
452                  END IF
453              END IF
454              BINEXP(I)=BINCTL(JTODAY,I)
455      92      CORRN=0.95*CORRN
456          IF(ITIME.EQ.1) GO TO 23
457          DO 93 I=1,(ITIME-1)

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458      IF(ITYPE.EQ.1) THEN
459          FTKEXP(I)=FTKCTL(JTOMOR,I)+CORRN
460          FSTEXP(I)=(GAMMA/(1.-GAMMA))*FTKEXP(I)
461      ELSE IF(ITYPE.EQ.2) THEN
462          FSTEXP(I)=GAMMA
463          IF(FSTEXP(I).GT.FINCTL(JTOMOR,I)) THEN
464              FSTEXP(I)=FINCTL(JTOMOR,I)+CORRN
465              FTKEXP(I)=0.0
466          ELSE
467              FTKEXP(I)=FTKCTL(JTOMOR,I)+CORRN
468          END IF
469      END IF
470      BINEXP(I)=BINCTL(JTOMOR,I)
471      93      CORRN=0.95*CORRN
472      23      DO 20 I=ITIME,(LAST-1)
473          DELPCV=(FTKEXP(I)-FOUTPR(I))/AMULT
474      20      PCVC(I+1)=PCVC(I)+DELPVC
475          IF(ITIME.EQ.1) GO TO 22
476          PCVC(1)=PCVC(LAST)
477          DO 21 I=1,(ITIME-2)
478              DELPCV=(FTKEXP(I)-FOUTPR(I))/AMULT
479      21      PCVC(I+1)=PCVC(I)+DELPVC
480      END IF
481      22      CALL ERCALC(FTKEXP,FSTEXP,FOUTPR,BINEXP,BOUTPR,PCVC,E(1),
482          1AMULT,ALPHA,BETA,OMEGA,TOPLIM,BOTLIM,LAST,ITIME,FOUTC,
483          2EFLOW,ELOAD,ELIM,EDIF)
484      C
485      C      SET-UP SCRATCH ARRAYS FOR PCVC AND FOUT
486      C
487      DO 30 I=1, LAST
488          PCVCT(I)=PCVC(I)
489      30      FOUTT(I)=FOUTPR(I)
490          ITERAT=24*NUMSIM/NUMCTL
491          DO 99 JCYC=1, NCYC
492              ICHFLG=0
493              ISTRT=ITIME-NUMCTL
494              IF(JCYC.NE.1) E(1)=E(ITERAT+1)
495          C
496          C      LOOP TO CARRY OUT PROFILE IMPROVEMENT
497          C
498              DO 110 I=1, ITERAT
499                  ISTRT=ISTRT+NUMCTL
500                  IF(ISTRT.EQ.LAST) ISTRT=1
501                  J=I+1
502          C
503          C      TRY A CHANGE IN THE PREVIOUS BEST DIRECTION
504          C
505              CHANGE=LIMIT*ISIGN(I)
506              CALL NEWPR(FOUTT,FTKEXP,PCVCT,CHANGE,AMULT,ISTRT,
507                  1ITIME,NUMCTL, LAST)
508          C
509          C      CHECK FOR NEGATIVE FOUTT VALUES
510          C
511              NEG=0
512              DO 40 K=1, LAST
513                  IF(FOUTT(K).LT.0.0) NEG=-1
514      40      CONTINUE

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```

515         IF (NEG.EQ.-1) THEN
516             E(J)=1.0E06
517         ELSE
518             CALL ERCALC(FTKEXP,FSTEXP,FOUTT,BINEXP,BOUTPR,PCVCT,E(J),
519 1  AMULT,ALPHA,BETA,OMEGA,TOPLIM,BOTLIM,LAST,ITIME,FOUTC,
520 2  EFLOW,ELOAD,ELIM,EDIF)
521         END IF
522         IF (E(J).LT.E(I)) GO TO 100
523     C
524     C     LOOP TO RE-INITIALIZE SCRATCH ARRAYS
525     C
526         DO 50 K=1, LAST
527             PCVCT(K)=PCVC(K)
528         50 FOUTT(K)=FOUTPR(K)
529     C
530     C     TRY A CHANGE IN THE OPPOSITE DIRECTION
531     C
532         ISIGN(I)=-ISIGN(I)
533         CHANGE=LIMIT*ISIGN(I)
534         CALL NEWPR(FOUTT,FTKEXP,PCVCT,CHANGE,AMULT,ISTR,
535 1 ITIME,NUMCTL, LAST)
536     C
537     C     CHECK FOR NEGATIVE VALUES OF FOUTT
538     C
539         NEG=0
540         DO 60 K=1, LAST
541             IF (FOUTT(K).LT.0.0) NEG=-1
542         60 CONTINUE
543         IF (NEG.EQ.-1) THEN
544             E(J)=1.0E06
545         ELSE
546             CALL ERCALC(FTKEXP,FSTEXP,FOUTT,BINEXP,BOUTPR,PCVCT,E(J),
547 1  AMULT,ALPHA,BETA,OMEGA,TOPLIM,BOTLIM, LAST,ITIME,FOUTC,
548 2  EFLOW,ELOAD,ELIM,EDIF)
549         END IF
550         IF (E(J).LT.E(I)) GO TO 100
551     C
552     C     LOOP TO RE-INITIALIZE SCRATCH ARRAYS
553     C
554         DO 70 K=1, LAST
555             PCVCT(K)=PCVC(K)
556         70 FOUTT(K)=FOUTPR(K)
557     C
558     C     TRY NO CHANGE
559     C
560         E(J)=E(I)
561         GO TO 110
562     C
563     C     RE-SET PCVC AND FOUTPR TO IMPROVED VALUE IF NECESSARY
564     C
565         100 DO 80 K=1, LAST
566             PCVC(K)=PCVCT(K)
567         80 FOUTPR(K)=FOUTT(K)
568         ICHFLG=ICHFLG+1
569         110 CONTINUE
570         IF (ICHFLG.LE.4) GO TO 98

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571      99      CONTINUE
572      98      INTVL=(ITIME+NUMCTL-1)/NUMCTL
573      FOUTC=FOUTPR(ITIME)
574      ITIME=ITIME+NUMCTL
575      PCVLS=PCV
576      RETURN
577      END
578      C*****
579      C
580      C      SUBROUTINE SUBCTL
581      C      -----
582      C
583      C      THIS SUBROUTINE IS AN EMERGENCY CONTROLLER
584      C      WHICH PREVENTS THE TANK LEVEL FROM BECOMING
585      C      LESS THAN 2%.
586      C
587      C*****
588      SUBROUTINE SUBCTL(PCVCUR,FOUTC,AMULT,FOUTRQ)
589      IF(PCVCUR.LT.2.0) THEN
590          LOWFLG=1
591          FIN=(PCVCUR-PCVPRV)*AMULT+FOUTM1
592          IF(FIN.LT.FOUTRQ) FOUTC=FIN
593      ELSE IF(LOWFLG.EQ.1) THEN
594          FOUTC=FOUTRQ
595          LOWFLG=0
596      END IF
597      PCVPRV=PCVCUR
598      FOUTM1=FOUTC
599      RETURN
600      END
601      C*****
602      C
603      C      SUBROUTINE NEWPR
604      C      -----
605      C
606      C*****
607      SUBROUTINE NEWPR(FOUTT,FTKEXP,PCVCT,CHANGE,AMULT,ISTRT,
608      1ITIME,NUMCTL,LAST)
609      PARAMETER N=289
610      DIMENSION FOUTT(N),PCVCT(N),FTKEXP(N)
611      IFIN=ISTRT+NUMCTL-1
612      DO 10 I=ISTRT,IFIN
613          10 FOUTT(I)=FOUTT(I)+CHANGE
614      DO 20 I=ITIME,(LAST-1)
615          DELPCV=(FTKEXP(I)-FOUTT(I))/AMULT
616          20 PCVCT(I+1)=PCVCT(I)+DELPV
617      IF(ITIME.EQ.1) RETURN
618      PCVCT(1)=PCVCT(LAST)
619      DO 30 I=1,(ITIME-2)
620          DELPCV=(FTKEXP(I)-FOUTT(I))/AMULT
621          30 PCVCT(I+1)=PCVCT(I)+DELPV
622      RETURN
623      END
624      C*****
625      C
626      C      SUBROUTINE ERCALC
627      C      -----

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641      C
642      C*****
643      SUBROUTINE ERCALC(FTKEXP,FSTEXP,FOUTPR,BINEXP,BOUTPR,PCV,
644      1ERROR,AMULT,ALPHA,BETA,OMEGA,TOPLIM,BOTLIM,LAST,ITIME,
645      2FOUTC,EFLOW,ELOAD,ELIM,EDIF)
646      PARAMETER N=289
647      REAL LOUT,LBAR,LSUM
648      DIMENSION FTKEXP(N),FOUTPR(N),BINEXP(N),BOUTPR(N),PCV(N)
649      DIMENSION FSTEXP(N)
650      DIMENSION FEXIT(N),LOUT(N),BEXIT(N)
651      LASTM1=LAST-1
652      FSUM=0.0
653      LSUM=0.0
654      C
655      C      CALCULATE TANK OUTLET CONCENTRATION
656      C      START CONVERGENCE CALCULATION WITH BOUTPR(1)=BINEXP(1)
657      C
658      BOUTPR(1)=BOUTPR(LAST)
659      C
660      DO 10 I=1,LASTM1
661      P1=(PCV(I)+PCV(I+1))/2.
662      IF(P1.GT.1.0) GO TO 40
663      BOUTPR(I+1)=BINEXP(I+1)
664      GO TO 10
665      40  BOUTPR(I+1)=BOUTPR(I)+FTKEXP(I)*((BINEXP(I)-BOUTPR(I))/(P1*AMULT))
666      10  CONTINUE
667      C
668      C      MIXING OF STREAMS
669      C
670      DO 20 I=1,LASTM1
671      FEXIT(I)=FSTEXP(I)+FOUTPR(I)
672      LOUT(I)=(FOUTPR(I)*BOUTPR(I)+FSTEXP(I)*BINEXP(I))
673      BEXIT(I)=LOUT(I)/FEXIT(I)
674      FSUM=FSUM+FEXIT(I)
675      LSUM=LSUM+LOUT(I)
676      20  CONTINUE
677      LBAR=LSUM/FLOAT(LASTM1)
678      FBAR=FSUM/FLOAT(LASTM1)
679      C
680      C      CALCULATE THE ERROR VALUE STARTING AT ITIME
681      C      AN ALTERNATIVE ERROR CALCULATION CAN BE USED
682      C
683      EFLOW=0.0
684      ELOAD=0.0
685      EDIF=0.0
686      ELIM=0.0
687      FPRV=FOUTC
688      DO 30 I=ITIME,LASTM1
689      P=FEXIT(I)/FBAR-1.0
690      Q=LOUT(I)/LBAR-1.0
691      EFLOW=EFLOW+P*P
692      ELOAD=ELOAD+Q*Q
693      EDIF=EDIF+(FOUTPR(I)-FPRV)**2
694      FPRV=FOUTPR(I)
695      IF(PCV(I).GT.(TOPLIM-6.0)) THEN
696      ELIM=ELIM+(PCV(I)-(TOPLIM-6.0))**6
697      ELSE IF(PCV(I).LT.(BOTLIM+6.0)) THEN

```

```

698         ELIM=ELIM+(PCV(I)-(BOTLIM+6.0))*6
699     END IF
700 30    CONTINUE
701     DO 50 I=1,(ITIME-1)
702     P=FEXIT(I)/FBAR-1.0
703     Q=LOUT(I)/LBAR-1.0
704     EFLOW=EFLOW+P*P
705     ELOAD=ELOAD+Q*Q
706     EDIF=EDIF+(FOUTPR(I)-FPRV)**2
707     FPRV=FOUTPR(I)
708     IF(PCV(I).GT.(TOPLIM-5.0)) THEN
709         ELIM=ELIM+(PCV(I)-(TOPLIM-5.0))*6
710     ELSE IF(PCV(I).LT.(BOTLIM+5.0)) THEN
711         ELIM=ELIM+(PCV(I)-(BOTLIM+5.0))*6
712     END IF
713 50    CONTINUE
714     ERROR=ALPHA*EFLOW+(1.0-ALPHA)*ELOAD+BETA*ELIM+OMEGA*EDIF
715     ERROR=ERROR/FLOAT(LASTM1)
716     EFLOW=ALPHA*EFLOW/FLOAT(LASTM1)
717     ELOAD=(1.0-ALPHA)*ELOAD/FLOAT(LASTM1)
718     ELIM=BETA*ELIM/FLOAT(LASTM1)
719     EDIF=OMEGA*EDIF/FLOAT(LASTM1)
720     RETURN
721     END

```

C.3 SIMCON - SIMULATION PROGRAM FOR THE CONTROLLED RESPONSE OF AN IN-LINE EQUALIZATION TANK

C.3.1 General Description

SIMCON is also an ASCII FORTRAN computer program and only differs from the program SIMCONOLD in that (1) only the response of an *in-line* equalization tank can be simulated, and (2) second order Range Kutta integration is used in the equalization algorithm section of the program to compute the expected response of the equalization tank. The General Description for the program SIMCONOLD (Section C.2.1) applies identically for the program SIMCON, and therefore is not repeated here.

C.3.2 A Typical Runstream for SIMCON

Most of the input data required for executing SIMCON is identical to that for SIMCONOLD (Section C.2.2). Therefore, the reader is again referred to the program listing in Section C.3.3 where details of the input data are documented.

An example of a typical runstream is as follows:

```

1      @RUN
2      @DELETE,C PF.
3      @ASG,UP PF.,F2
4      @SYM,D PRINT$
5      @BRKPT PRINT$/PF
6      @XQT CMASP*EQUAL.SIMCONABS
7      5.5
8      95.0 5.0
9      0.5 2.0E-06 20.0
10     2
11     12
12     0.02
13     1 1 2
14     @ADD CMASP*EQUAL.FIN1
15     @ADD CMASP*EQUAL.BIN1
16     @ADD CMASP*EQUAL.FIN2
17     @ADD CMASP*EQUAL.BIN2
18     92.0 971.0
19     @ADD CMASP*EQUAL.FLOWCONCDATA
20     -99.9 999.9
21     @COPY,I 21.,CMASP*EQUAL.PLOTDATA
22     @ED CMASP*EQUAL.PLOTDATA,.PLOTDATA
23     @BRKPT PRINT$
24     @SYM,D PRINT$
25     @FREE PF.
```

The printed output obtained from execution of SIMCON is identical to that shown in Section C.2.2 for the program SIMCONOLD.

C.3.3 Listing of Program SIMCON

CMASP*EQUAL(1).SIMCON

```

1      C*****
2      C
3      C      PROGRAM TO SIMULATE OPERATION OF CONTROL STRATEGY      C
4      C      -----      C
5      C
6      C      THIS PROGRAM SIMULATES THE CONTROLLED RESPONSE OF AN      C
7      C      IN-LINE EQUALIZATION TANK UNDER SPECIFIED INPUTS OF      C
8      C      FLOW RATE AND CONCENTRATION WHEN THE OUTFLOW RATE FROM      C
9      C      THE TANK IS DETERMINED THROUGH APPLICATION OF THE      C
10     C      EQUALIZATION CONTROL STRATEGY DEVELOPED AT THE UNIV.      C
11     C      OF CAPE TOWN.      C
12     C      C
13     C*****
14     C      NOTE: IN THAT PART OF THE PROGRAM WHICH INVOLVES THE      C
15     C      EQUALIZATION ALGORITHM, 2ND ORDER RUNGE-KUTTA      C
16     C      INTEGRATION IS USED TO COMPUTE THE TANK HOLD-UP      C
17     C      AND CONCENTRATION RESPONSE. THIS METHOD IS ALSO      C
18     C      USED TO COMPUTE THE RESPONSE OF THE 'REAL' TANK      C
19     C      UNDER THE SPECIFIED INPUTS OF FLOW RATE AND CONC.      C
20     C*****
21     C
22     C      DETAILS FOR DATA INPUT (ALL DATA IN FREE FORMAT)      C
23     C      -----      C
24     C
25     C      CARD 1 : THT - MEAN TANK RETENTION TIME(HOURS)      C
26     C      E.G. 6.0      C
27     C
28     C      CARD 2 : TOPLIM,BOTLIM - UPPER AND LOWER ALLOWABLE TANK      C
29     C      HOLD-UP LIMITS(%)      C
30     C      E.G. 95.0 5.0      C
31     C
32     C      CARD 3 : ALPHA,BETA,OMEGA - ERROR EXPRESSION WEIGHTING      C
33     C      FACTORS      C
34     C      E.G. 0.5 2.0E-06 25.0      C
35     C
36     C      CARD 4 : NI - NO. OF CONTROL INTERVALS PER HOUR      C
37     C      E.G. 2      C
38     C
39     C      CARD 5 : NR - NO. OF SIMULATION INTERVALS PER HOUR FOR      C
40     C      'REAL' TANK      C
41     C      E.G. 12      C
42     C
43     C      CARD 6 : LIMIT - SIZE OF INCREMENTAL CHANGE MADE TO      C
44     C      FLOW RATE BY EQUALIZATION ALGORITHM      C
45     C      E.G. 0.02      C
46     C
47     C      CARD 7 : JTODAY,JTOMOR,JNEXT - DAY-TYPES FOR TODAY,      C
48     C      TOMORROW AND NEXT DAY      C
49     C      =1 FOR WEEKDAY      C
50     C      =2 FOR WEEKEND DAY      C
51     C      E.G. 1 1 2      C
52     C
53     C      CARD 8 : ENTER 'NI*24' HISTORICAL VALUES OF THE MEAN      C
54     C      FLOW RATE FOR EACH CONTROL INTERVAL DURING A      C
55     C      WEEKDAY      C
56     C      E.G. @ADD EQUAL.FIN1      C

```

```

57      C
58      C      CARD 9 : ENTER 'NI*24+1' POINT VALUES OF HISTORICAL      C
59      C      CONCENTRATION DATA CORRESPONDING TO START AND          C
60      C      FINISH OF EACH CONTROL INTERVAL IN A WEEKDAY            C
61      C      E.G. @ADD EQUAL.BIN1                                     C
62      C
63      C      CARD 10: ENTER 'NI*24' HISTORICAL VALUES OF THE MEAN    C
64      C      FLOW RATE FOR EACH CONTROL INTERVAL DURING A           C
65      C      WEEKEND                                                  C
66      C      E.G. @ADD EQUAL.FIN2                                     C
67      C
68      C      CARD 11: ENTER 'NI*24+1' POINT VALUES OF HISTORICAL    C
69      C      CONCENTRATION DATA CORRESPONDING TO START AND          C
70      C      FINISH OF EACH CONTROL INTERVAL IN A WEEKEND            C
71      C      E.G. @ADD EQUAL.BIN2                                     C
72      C
73      C      CARD 12: PCV(1),BOUTA - INITIAL TANK HOLD-UP AND         C
74      C      CONCENTRATION AT START OF SIMULATION                   C
75      C      E.G. 90.0 870.0                                         C
76      C
77      C      CARD 13: ACTUAL INFLOW RATE AND CONCENTRATION AT         C
78      C      START OF SIMULATION                                     C
79      C      E.G. 41.0 865.0                                         C
80      C
81      C      CARD 14: POINT VALUES OF ACTUAL INFLOW RATE AND         C
82      C      CONCENTRATION AT INTERVALS OF '60/NR'                   C
83      C      MINUTES AFTER START                                     C
84      C      E.G. 41.5 876.0                                         C
85      C      43.7 830.0                                              C
86      C      40.5 890.0                                              C
87      C
88      C      CARD 15: -99.9 99.9 - STOPPING CARD                     C
89      C
90      C      UNITS : ANY UNITS FOR BOTH FLOW RATE AND CONCENTRATION   C
91      C      PROVIDING THE UNITS ARE COMPATIBLE                       C
92      C
93      C*****
94      C      PARAMETER ND=2
95      C      PARAMETER NE=48
96      C      PARAMETER NF=49
97      C      COMMON/B1/FINHS(ND,NE),BINHS(ND,NF),ISIGN(NE),PCV(ND)
98      C      COMMON/B2/BOUTC(NF),E(NF)
99      C      COMMON/B3/THT,TOPLIM,BOTLIM,ALPHA,BETA,OMEGA,LIMIT,
100     1      JTDAY,JTOMOR,JNEXT,LAST,AMULT,DTC,FOUTC,
101     2      EFLOW,ELOAD,ELIM,EDIF,DTCOA,ITIME,LASTM1
102     DIMENSION FINACT(2),BINACT(2)
103     REAL LOUTC,LOUTA,LIMIT,LASTM1
104     CALL UNDSCT(3)
105     CALL DIVSET(3)
106     CALL OVFSCT(3)
107     CALL OVUNFL(3)
108     C
109     50  FORMAT( )
110     150  FORMAT(3X,F4.1,4X,F5.3,4X,F6.1,6X,F4.1,8X,5(F6.4,2X),9X,I2)
111     250  FORMAT(5(F9.3))
112     350  FORMAT(////5X,20('*')/6X,'SIMULATION RESULTS'/5X,20('*')
113     1//3X,'TIME  OUTFLOW  EFF.  LOAD  TANK %',18X,
114     2'ERROR DISTRIBUTION',18X,'NO. OF'

```

```

115      3/2X, '(HRS.)   RATE   RATE   HOLD-UP   FLOW   ',
116      4'LOAD   LIMIT   DF/DT   TOTAL   ITERATIONS'
117      5/2X, 6(' '), 4X, 4(' '), 5X, 4(' '), 6X, 7(' '), 8X, 4(' '),
118      64X, 4(' '), 3X, 5(' '), 3X, 5(' '), 3X, 5(' '), 7X, 10(' ') /
119      450   FORMAT(1H1, 4X, 12('*') / 6X, 'INPUT DATA' / 5X, 12('*'))
120      550   FORMAT(/ / 3X, 'MEAN TANK RETENTION TIME (HOURS) = ', F3.1
121      1 / 3X, 'TANK VOLUME LIMITS (%) : / 10X, 'MAXIMUM = ', F4.1 /
122      210X, 'MINIMUM = ', F4.1 / 3X, 'ERROR EXPRESSION WEIGHTING ',
123      3'FACTORS : / 10X, 'ALPHA = ', F4.2 / 10X, 'BETA = ', E7.1 / 10X,
124      4'OMEGA = ', F4.1 / 3X, 'MINIMUM FLOW ADJUSTMENT = ', F4.2 /
125      53X, 'SEQUENCE OF DAY TYPES : ')
126      650   FORMAT(/ 10X, 'WEEKDAY')
127      750   FORMAT(/ 10X, 'WEEKEND DAY')
128      C
129      C   READ IN DATA
130      C
131      READ(8, 50) THT
132      READ(8, 50) TOPLIM, BOTLIM
133      READ(8, 50) ALPHA, BETA, OMEGA
134      READ(8, 50) NI
135      READ(8, 50) NR
136      READ(8, 50) LIMIT
137      READ(8, 50) JTODAY, JTOMOR, JNEXT
138      C
139      C   WRITE OUT INPUT DATA
140      C
141      WRITE(5, 450)
142      WRITE(5, 550) THT, TOPLIM, BOTLIM, ALPHA, BETA, OMEGA, LIMIT
143      IF(JTODAY.EQ.1) WRITE(5, 650)
144      IF(JTODAY.EQ.2) WRITE(5, 750)
145      IF(JTOMOR.EQ.1) WRITE(5, 650)
146      IF(JTOMOR.EQ.2) WRITE(5, 750)
147      IF(JNEXT.EQ.1) WRITE(5, 650)
148      IF(JNEXT.EQ.2) WRITE(5, 750)
149      C
150      C   TO INITIALIZE SOME ARRAYS
151      C
152      LAST=NI*24+1
153      LASTM1=FLOAT(LAST-1)
154      DO 40 I=1, (LAST-1)
155      ISIGN(I)=1
156      40   E(I)=1.0E06
157      E(LAST)=1.0E06
158      C
159      C   READ IN VARIABLES REQUIRED BY THE CONTROL ALGORITHM.
160      C   READ 'LAST-1' VALUES OF MEAN HISTORICAL INFLUENT FLOW
161      C   RATE FOR EACH CONTROL INTERVAL AND 'LAST' POINT VALUES
162      C   OF CONCENTRATION FOR EACH DAY TYPE.
163      C
164      DO 30 J=1, 2
165      READ(8, 50) (FINHST(J, I), I=1, (LAST-1))
166      READ(8, 50) (BINHST(J, I), I=1, LAST)
167      30   CONTINUE
168      C
169      C   NORMALIZE FLOW VALUES FOR EACH DAY TYPE
170      C
171      FSUM=0.0

```

```

172      DO 20 I=1,(LAST-1)
173      20  FSUM=FSUM+FINHST(1,I)
174      FBAR=FSUM/LASTM1
175      DO 60 J=1,2
176      DO 70 I=1,(LAST-1)
177      70  FINHST(J,I)=FINHST(J,I)/FBAR
178      60  CONTINUE
179      C
180      C   READ INITIAL VALUE OF PCV AND BOUT
181      C
182      READ(8,50) PCV(1),BOUTA
183      C
184      C   READ AND 'NORMALIZE' ACTUAL INFLOW
185      C   AND READ ACTUAL INFLUENT CONCENTRATION
186      C   AT START OF SIMULATION
187      C
188      READ(8,50) FINACT(1),BINACT(1)
189      FINACT(1)=FINACT(1)/FBAR
190      C
191      C   INITIAL SET-UP
192      C
193      AMULT=THT/100.
194      NCTL=NR/NI
195      JKTCTL=NCTL
196      BOUTC(1)=BOUTA
197      DTC=1./FLOAT(NI)
198      DTR=1./FLOAT(NR)
199      DTDOA=DTC/AMULT
200      WRITE(5,350)
201      C
202      C   BEGIN ITERATION
203      C
204      1001 CONTINUE
205      JKTCTL=JKTCTL+1
206      C
207      C   SET TANK OUTFLOW EVERY NCTL REAL TANK SIM. INTS.
208      C
209      IF(JKTCTL.LT.NCTL) GO TO 500
210      JKTCTL=0
211      CALL CONTRL(JCYC)
212      FOUTRQ=FOUTC
213      500 CONTINUE
214      CALL SUBCTL(PCV(1),AMULT,DTR,FOUTC,FOUTRQ)
215      FOUTA=FOUTC
216      C
217      C   REAL TANK SIMULATION
218      C
219      C
220      C   READ AND 'NORMALISE' THE ACTUAL INFLOW
221      C   AND READ ACTUAL INFLUENT CONCENTRATION
222      C   AT END OF EACH NUMSIM INTERVAL
223      C
224      READ(8,50) FINACT(2),BINACT(2)
225      C
226      C   STOPPING CONDITION
227      C
228      IF(FINACT(2).LT.0.0) CALL EXIT

```



```

229      FINACT(2)=FINACT(2)/FBAR
230      C
231      C      OUTPUT RESULTS ON MAKING A CONTROL DECISION
232      C
233      LOUTA=FOUTA*BOUTA
234      IF(JKTCTL.EQ.0) THEN
235          CTIME=FLOAT(ITIME-2)*DTC
236          WRITE(5,150) CTIME,FOUTA,LOUTA,PCV(1),EFLOW,ELOAD,
237      1  ELIM,EDIF,E(LAST),JCYC
238      END IF
239      C
240      C      STORE RESULTS FOR PLOTTING
241      C
242      WRITE(21,250) FINACT(1),BINACT(1),PCV(1),FOUTA,LOUTA
243      C
244      C      DETERMINE PCV(2) AND BOUTA
245      C
246      FMID=(FINACT(1)+FINACT(2))/2.
247      PCV(2)=PCV(1)+DTR*(FMID-FOUTA)/AMULT
248      IF(PCV(2).LT.0.5) THEN
249          PCV(2)=PCV(1)
250          IF(FOUTA.GT.FINACT(2)) FOUTA=FINACT(2)
251      END IF
252      IF(PCV(2).GT.100.0) THEN
253          PCV(2)=100.0
254          IF(FOUTA.LT.FINACT(2)) FOUTA=FINACT(2)
255      END IF
256      IF(PCV(2).LT.1.0) THEN
257          BOUTA=BINACT(2)
258      ELSE
259          CALL RKREAL(FINACT(1),FINACT(2),DTR,BINACT(1),BINACT(2),
260      1  PCV(1),AMULT,FOUTA,BOUTA,CONC)
261          IF(CONC.LT.0.0) CONC=BINACT(2)
262          BOUTA=CONC
263      END IF
264      FINACT(1)=FINACT(2)
265      BINACT(1)=BINACT(2)
266      PCV(1)=PCV(2)
267      GO TO 1001
268      END
269      C*****
270      C
271      C      SUBROUTINE CONTRL
272      C      -----
273      C
274      C      THIS SUBROUTINE SUPPLIES THE SETTING FOR THE TANK
275      C      OUTLET RATE
276      C
277      C*****
278      SUBROUTINE CONTRL(JCYC)
279      PARAMETER ND=2
280      PARAMETER NE=48
281      PARAMETER NF=49
282      COMMON/B1/FINHST(ND,NE),BINHST(ND,NF),ISIGN(NE),PCV(ND)
283      COMMON/B2/BOUTC(NF),E(NF)
284      COMMON/B3/THI,TOPLIM,BOTLIM,ALPHA,BETA,OMEGA,LIMIT,
285      1  JTODAY,JTOMOR,JNEXT,LAST,AMULT,DTC,FOUTC,

```

```

286      2      EFLOW,ELOAD,ELIM,EDIF,ITCOA,ITIME,LASTM1
287      COMMON/B4/FINEXP(NE),BINEXP(NF),PCVCT(NF),PCVC(NF),
288      1      FOUT(NE),FOUTC(NE),LOUTC(NE)
289      REAL LIMIT,LOUTC
290      IF(INITL.EQ.0) THEN
291          NCYC=30
292          ITIME=1
293          DO 10 I=1,(LAST-1)
294      10      FOUT(I)=1.0
295          FOUTC=FOUT(1)
296          PCVC(1)=PCV(1)
297          DO 90 I=1,(LAST-1)
298          FINEXP(I)=FINHST(JTODAY,I)
299          BINEXP(I)=BINHST(JTODAY,I)
300      90      CONTINUE
301          BINEXP(LAST)=BINHST(JTODAY,LAST)
302          DELFCT=0.0
303          INITL=10
304      ELSE
305          NCYC=15
306          FLAST=FOUT(1)
307          DO 20 I=1,(LAST-2)
308          FOUT(I)=FOUT(I+1)
309      20      CONTINUE
310          FOUT(LAST-1)=FLAST
311          FINXM=FINHST(JTODAY,ITIME-1)
312          IF(ITIME.EQ.LAST) THEN
313              ITIME=1
314              JTODAY=JTMOR
315              JTMOR=JNEXT
316          END IF
317          PCVC(1)=PCV(1)
318          FINAM=FOUTC+(PCV(1)-PCVLST)*AMULT/DTC
319          IF(PCV(1).EQ.100.0.AND.PCVLST.EQ.100.0) FINAM=1.5*FINXM
320          DELFCT=0.4*DELFCT+0.6*(FINAM-FINXM)
321          CORRN=DELFCT
322          DO 92 I=ITIME,(LAST-1)
323          FINEXP(I-ITIME+1)=FINHST(JTODAY,I)+CORRN
324          BINEXP(I-ITIME+1)=BINHST(JTODAY,I)
325          CORRN=0.3*CORRN
326      92      CONTINUE
327          BINEXP(LAST-ITIME+1)=BINHST(JTODAY,LAST)
328          IF(ITIME.EQ.1) GO TO 23
329          DO 93 I=2,ITIME
330          FINEXP(I-ITIME+LAST-1)=FINHST(JTMOR,I-1)+CORRN
331          BINEXP(I-ITIME+LAST)=BINHST(JTMOR,I)
332          CORRN=0.3*CORRN
333      93      CONTINUE
334      END IF
335      23      DO 91 I=1,(LAST-1)
336          PCVC(I+1)=PCVC(I)+DTCOA*(FINEXP(I)-FOUT(I))
337      91      CONTINUE
338      C
339      C      SET-UP SCRATCH ARRAY FOR FOUT
340      C
341      DO 30 I=1,(LAST-1)
342          PCVCT(I)=PCVC(I)

```

```

343      30      FOUTT(I)=FOUT(I)
344              PCVCT(LAST)=PCVC(LAST)
345      C
346      C      CALCULATE INITIAL ERROR VALUE
347      C
348              CALL ERCALC(1,ERROR)
349              E(1)=ERROR
350      DO 99 JCYC=1,NCYC
351          ICHFLG=0
352          IF(JCYC.NE.1) E(1)=E(LAST)
353      C
354      C      LOOP TO CARRY OUT PROFILE IMPROVEMENT
355      C
356          DO 110 IC=1,(LAST-1)
357              JC=IC+1
358      C
359      C      TRY A CHANGE IN THE PREVIOUS BEST DIRECTION
360      C
361              CHANGE=LIMIT*ISIGN(IC)
362              CALL NEWPR(IC,CHANGE,DTCOA,LAST)
363              CALL ERCALC(IC,ERROR)
364              E(JC)=ERROR
365              IF(E(JC).LT.E(IC)) GO TO 100
366      C
367      C      TRY A CHANGE IN THE OPPOSITE DIRECTION
368      C
369              ISIGN(IC)=-ISIGN(IC)
370              CHANGE=LIMIT*ISIGN(IC)
371              CALL NEWPR(IC,CHANGE,DTCOA,LAST)
372              CALL ERCALC(IC,ERROR)
373              E(JC)=ERROR
374              IF(E(JC).LT.E(IC)) GO TO 100
375      C
376      C      ACCEPT NO CHANGE
377      C
378              E(JC)=E(IC)
379              FOUTT(IC)=FOUT(IC)
380              PCVCT(IC+1)=PCVC(IC+1)
381              GO TO 110
382      C
383      C      RE-SET FOUT AND PCVC TO IMPROVED VALUE IF NECESSARY
384      C
385      100      FOUT(IC)=FOUTT(IC)
386              DO 40 I=IC,(LAST-1)
387                  PCVC(I+1)=PCVCT(I+1)
388                  ICHFLG=ICHFLG+1
389                  BNEXT=BOUTC(ITIME+1)
390      110      CONTINUE
391              IF(ICHFLG.LE.4) GO TO 98
392      99      CONTINUE
393      98      FOUTC=FOUT(1)
394              ITIME=ITIME+1
395              BOUTC(1)=BNEXT
396              PCVLST=PCV(1)
397              RETURN
398      END

```

```

399 C*****
400 C
401 C   SUBROUTINE SUBCTL
402 C   -----
403 C
404 C   THIS SUBROUTINE IS AN EMERGENCY CONTROLLER
405 C   WHICH PREVENTS THE TANK LEVEL FROM BECOMING
406 C   LESS THAN 2%.
407 C
408 C*****
409 C   SUBROUTINE SUBCTL(PCVCUR,AMULT,DTR,FOUTC,FOUTRQ)
410 C   IF(PCVCUR.LT.2.0) THEN
411 C       LOWFLG=1
412 C       FIN=AMULT*(PCVCUR-PCVPRV)/DTR+FOUTM1
413 C       IF(FIN.LT.FOUTRQ) FOUTC=FIN
414 C   ELSE IF(LOWFLG.EQ.1) THEN
415 C       FOUTC=FOUTRQ
416 C       LOWFLG=0
417 C   END IF
418 C   PCVPRV=PCVCUR
419 C   FOUTM1=FOUTC
420 C   RETURN
421 C   END
422 C*****
423 C
424 C   SUBROUTINE NEWPR
425 C   -----
426 C
427 C*****
428 C   SUBROUTINE NEWPR(IC,CHANGE,DTCOA,LAST)
429 C   PARAMETER NE=48
430 C   PARAMETER NF=49
431 C   COMMON/B4/FINEXP(NE),BINEXP(NF),PCVCT(NF),PCVC(NF),
432 C   1      FOUT(NE),FOUTT(NE),LOUTC(NE)
433 C   FOUTT(IC)=FOUT(IC)+CHANGE
434 C   DELP=-DTCOA*CHANGE
435 C   DO 10 I=IC,(LAST-1)
436 C       PCVCT(I+1)=PCVC(I+1)+DELP
437 C   10 CONTINUE
438 C   RETURN
439 C   END
440 C*****
441 C
442 C   SUBROUTINE ERCALC
443 C   -----
444 C
445 C*****
446 C   SUBROUTINE ERCALC(IC,ERROR)
447 C   PARAMETER NE=48
448 C   PARAMETER NF=49
449 C   COMMON/B2/BOUTC(NF),E(NF)
450 C   COMMON/B3/THT,TOTPLIM,BOTLIM,ALPHA,BETA,OMEGA,LIMIT,
451 C   1      JTODAY,JTOMOR,JNEXT,LAST,AMULT,DTC,FOUTC,
452 C   2      EFLOW,ELOAD,ELIM,EDIF,DTCOA,ITIME,LASTM1
453 C   COMMON/B4/FINEXP(NE),BINEXP(NF),PCVCT(NF),PCVC(NF),
454 C   1      FOUT(NE),FOUTT(NE),LOUTC(NE)
455 C   REAL LBAR,LSUM,LOUTC,LASTM1

```

```

456      FSUM=0.0
457      LSUM=0.0
458      IF(IC.EQ.1) THEN
459          K=1
460          SEFLOW=0.0
461          SELOAD=0.0
462          SELIM=0.0
463          SEDIF=0.0
464          ICLAST=1
465      END IF
466      IF(IC.GT.1) THEN
467          K=IC-1
468          FPRV=FOUTT(K-1)
469      END IF
470      IF(IC.GT.1.AND.IC.EQ.ICLAST) THEN
471          K=IC
472          FPRV=FOUTT(K-1)
473      END IF
474      IF(K.EQ.1) FPRV=FOUTC
475      TOPM5=TOPLIM-5.0
476      BOTP5=BOTLIM+5.0
477      C
478      C      CALCULATE TANK OUTLET CONCENTRATION
479      C
480      DO 10 I=K,(LAST-1)
481      IF(PCVCT(I+1).LT.0.5) THEN
482          BOUTC(I+1)=BINEXP(I+1)
483      ELSE
484          CALL RKCON(FINEXP(I),AMULT,BINEXP(I),BINEXP(I+1),DTC,
485      1          PCVCT(I),FOUTT(I),BOUTC(I),CONC)
486          IF(CONC.LT.0.0) CONC=BINEXP(I+1)
487          BOUTC(I+1)=CONC
488      END IF
489      10  CONTINUE
490      C
491      C      CALCULATE MEAN FLOW AND LOAD
492      C
493      DO 30 I=1,(LAST-1)
494          BMID=(BOUTC(I)+BOUTC(I+1))/2.
495          LOUTC(I)=FOUTT(I)*BMID
496          LSUM=LSUM+LOUTC(I)
497      30  FSUM=FSUM+FOUTT(I)
498          FBAR=FSUM/LASTM1
499          LBAR=LSUM/LASTM1
500      C
501      C      CALCULATE THE INDIVIDUAL ERROR VALUES
502      C
503          EFLOW=SEFLOW
504          ELOAD=SELOAD
505          EDIF=SEDIF
506          ELIM=SELIM
507      DO 40 I=K,(LAST-1)
508          P=FOUTT(I)/FBAR-1.0
509          Q=LOUTC(I)/LBAR-1.0
510          EFLOW=EFLOW+P*P
511          ELOAD=ELOAD+Q*Q
512          EDIF=EDIF+(FOUTT(I)-FPRV)**2

```

```

513         IF (IC.NE.ICLAST.AND.I.EQ.K) THEN
514             SEFLOW=EFLOW
515             SELOAD=ELOAD
516             SEDIF=EDIF
517         END IF
518     40     FPRV=FOUTT(I)
519         DO 50 I=K, LAST
520             IF (PCVCT(I).GT.TOPM5) ELIM=ELIM+(PCVCT(I)-TOPM5)**6
521             IF (PCVCT(I).LT.BOTP5) ELIM=ELIM+(PCVCT(I)-BOTP5)**6
522             IF (IC.NE.ICLAST.AND.I.EQ.K) SELIM=ELIM
523     50     CONTINUE
524         ICLAST=IC
525     C
526     C     TOTAL ERROR
527     C
528         EFLOW=ALPHA*EFLOW/LASTM1
529         ELOAD=(1.-ALPHA)*ELOAD/LASTM1
530         ELIM=BETA*ELIM/LASTM1
531         EDIF=OMEGA*EDIF/LASTM1
532         ERROR=EFLOW+ELOAD+ELIM+EDIF
533         RETURN
534     END
535 C*****
536 C
537 C     SUBROUTINE RKREAL
538 C     -----
539 C
540 C*****
541     SUBROUTINE RKREAL(A,FINTP1,DT,C,CINTP1,PCVT,AMULT,FOUT,
542     1     COUTT,CONC)
543     REAL K1,K2
544     FUNC1(X1,Y1)=(A+B*X1)*(C+D*X1-Y1)/(E+F*X1+G*X1*X1)
545     B=(FINTP1-A)/DT
546     D=(CINTP1-C)/DT
547     E=PCVT*AMULT
548     F=A-FOUT
549     G=B/2.
550     X=0.0
551     Y=COUTT
552     K1=FUNC1(X,Y)
553     X=DT
554     Y=COUTT+DT*K1
555     K2=FUNC1(X,Y)
556     CONC=COUTT+DT*(K1+K2)/2.
557     RETURN
558     END
559 C*****
560 C
561 C     SUBROUTINE RKCON
562 C     -----
563 C
564 C*****
565     SUBROUTINE RKCON(FIN,AMULT,B,CINTP1,DT,D,FOUT,COUTT,CONC)
566     REAL K1,K2
567     FUNC2(X1,Y1)=A*(B+C*X1-Y1)/(D+E*X1)
568     A=FIN/AMULT
569     C=(CINTP1-B)/DT

```

```
570      E=(FIN-FOUT)/AMULT
571      X=0.0
572      Y=COUIT
573      K1=FUNC2(X,Y)
574      X=DT
575      Y=COUIT+DT*K1
576      K2=FUNC2(X,Y)
577      CONC=COUIT+DT*(K1+K2)/2.
578      RETURN
579      END
```

C.4 CONPLOT - PLOTTING PROGRAM FOR SIMULATION RESULTS

A single plotting program CONPLOT was written for the graphical output of simulation results from execution of either of the two simulation programs, SIMCON or SIMCONOLD. The program is based on the CALCOMP plotting software and makes use of a number of subroutines listed in Appendix B. A listing of the program is supplied here, together with details of the required input data and instructions for execution, for the benefit of users who possibly have access to the same software.

C.4.1 A Typical Runstream for CONPLOT

During execution of either of the simulation programs certain results are written to a temporary file (No.21). It is assumed here that, on completion of execution, this data has been transferred to a data element EQUAL.PLOTDATA. The number of lines of data in this element will be one less than the number of point values of flow rate and concentration used during the simulation, i.e. 576, when point values at 5 minute intervals over a 2 day period are used.

The program CONPLOT is compiled and mapped together with the elements CMASP*EQUAL.NLINE, .NAXIS, .PAGSIZ, .BRLINE and .SCRIBE in the manner described in Section B.2 to provide an executable absolute version of the program in the element CMASP*EQUAL.CONPLOTM. An example listing of the runstream is provided overleaf; the user's attention is drawn to information peculiar to each execution which must be supplied by the user.

CMASP*EQUAL(1).RUNCONPLOT

```

1  @GDP*ABS.INPUT DOLDPLOT.
2  @XQT,F CMASP*EQUAL.CONPLOTABS
3  16.00 28.00 0.0 3.0 0.0 0.286
4  0.60
5  7
6  576
7  EXPECTED FLOW AND LOAD VALUES
8  @ADD CMASP*EQUAL.FIN1
9  @ADD CMASP*EQUAL.FIN1
10 @ADD CMASP*EQUAL.LIN1
11 @ADD CMASP*EQUAL.LIN1
12 FINACT,BINACT,PCV,FOUT,LOUT VALUES
13 @ADD CMASP*EQUAL.PLOTDATA
14 -1.0 0.0 0.30 0.0 0.0
15 -1.0 3.35 0.30 0.0 0.5
16 -1.0 6.7 0.30 0.0 1.0
17 -1.0 8.6 0.30 0.0 0.5
18 -1.0 10.35 0.30 0.0 1.0
19 -1.0 12.1 0.30 0.0 1.5
20 -1.0 13.8 0.30 0.0 0.0
21 -1.0 15.6 0.30 0.0 0.5
22 -1.0 17.4 0.30 0.0 1.0
23 -1.0 19.1 0.30 0.0 1.5
24 -1.0 20.8 0.30 0.0 0.0
25 -1.0 22.6 0.30 0.0 0.5
26 -1.0 24.4 0.30 0.0 1.0
27 -1.0 26.1 0.30 0.0 1.5
28 -1.0 27.7 0.30 0.0 2.0
29 0.0 -0.5 0.30 0.0 0
30 1.9 -0.5 0.30 0.0 6
31 3.8 -0.5 0.30 0.0 12
32 5.8 -0.5 0.30 0.0 18
33 7.8 -0.5 0.30 0.0 24
34 9.8 -0.5 0.30 0.0 6
35 11.8 -0.5 0.30 0.0 12
36 13.8 -0.5 0.30 0.0 18
37 15.5 -0.5 0.30 0.0 24
38 5.2 22.2 0.30 0.0 HISTORICAL
39 9.5 27.0 0.30 0.0 ACTUAL
40 5.0 15.2 0.30 0.0 HISTORICAL
41 9.5 20.0 0.30 0.0 ACTUAL
42 1.2 11.9 0.30 0.0 FLOW
43 4.8 8.2 0.30 0.0 LOAD
44 6.2 -2.0 0.3 0.0 TIME (HOURS)
45 3.0 -1.5 0.25 0.0 DAY1
46 11.0 -1.5 0.25 0.0 DAY2
47 -1.5 8.0 0.3 90.0 FLOW AND LOAD OUT
48 -1.5 23.4 0.3 90.0 FLOW IN
49 -1.5 16.4 0.3 90.0 LOAD IN
50 -1.5 0.2 0.3 90.0 FRACTIONAL TANK VOLUME
51 0.6 30.2 0.35 0.0 CONFIGURATION : IN-LINE
52 0.6 29.6 0.30 0.0 TANK HOLD-UP = 5.5 HOURS
53 0.6 29.0 0.30 0.0 TANK LIMITS MAX = 95.0%
54 0.6 28.4 0.30 0.0 MIN = 5.0%
55 10.5 29.6 0.30 0.0 EQ. ERROR WT.:
56 11.0 29.0 0.30 0.0 ALPHA = 0.50
57 999.

```

```

← *
← *
← *
← *
← *

```

C.4.2 Listing of Program CONPLOT

CMASP*EQUAL(1).CONPLOT

```

1      C*****
2      C
3      C    PLOTTER PROGRAM FOR CONTROL RESULTS    C
4      C    -----                                C
5      C
6      C*****
7      C    PARAMETER NDIM=600
8      C    INTEGER YTITLE(10),XTITLE(10)
9      C    REAL LBAR,LSUM
10     C    DIMENSION FLABEL(20)
11     C    USE X1,X2,X3 IF REQUIRED
12     C    DIMENSION XVALS(NDIM),Y1VALS(NDIM),Y2VALS(NDIM),Y3VALS(NDIM),
13     C    Y4VALS(NDIM),Y5VALS(NDIM),Y6VALS(NDIM),Y7VALS(NDIM),SEGL1(2)
14     C    2,SEGL2(4)
15     C    DATA SEGL1/0.3,0.2/
16     C    DATA SEGL2/0.3,0.2,0.05,0.2/
17     C..
18     10  FORMAT( )
19     505  FORMAT(20A4)
20     506  FORMAT(10A4,10A4)
21     C
22     C    NCR=8
23     C    NPR=5
24     C
25     C    WRITE(NPR,510)
26     510  FORMAT(' ENTER LENGTHS OF X AND Y SCALES, AND
27     C    $// SCALEDATA FOR X, THEN FOR Y.',
28     C    $// '(SCALDATA IN FORM: FIRST VALUE, UNITS/CM)',
29     C    $// ' ENTER SCALING FACTOR')
30     C    READ(NCR,10)XLONG,YHIGH,SCALX1,SCALX2,SCALY1,SCALY2,FCTR
31     C
32     C..  START PLOT
33     C    CALL PLOTS(0,0,0)
34     C    CALL NEWPEN(1)
35     C    CALL OPMES(24,'PLEASE LOAD P1-BK/I4  ')
36     C    CALL FACTOR(FCTR)
37     C    A1=(XLONG+2.)*FCTR
38     C    A2=(YHIGH+3.)*FCTR
39     C    CALL PAGDEF(-2.,-3.,A1,A2)
40     C
41     C..  READ THE NUMBER OF LINES PER GRAPH
42     C    WRITE(NPR,530)
43     530  FORMAT(' ENTER NO OF DATA SETS TO BE PLOTTED')
44     C    READ(NCR,10) KLINE
45     C    WRITE(NPR,540)KLINE
46     540  FORMAT(' ENTER THE',I2,' DATA SETS '//
47     C    1' LABEL'//
48     C    2' @ADD ELT WITH DATA')
49     C..  READ NUMBER OF DATA POINTS
50     C    READ(NCR,10) ND
51     C
52     C    CREATE THE X DATA
53     C
54     C    DELX=48./FLOAT(ND)
55     C    SCALX1=DELX/2.
56     C    XVALS(1)=SCALX1

```

```

57      DO 30 I=1,(ND-1)
58      30  XVALS(I+1)=XVALS(I)+DELX
59      C
60      C      READ THE Y DATA
61      READ(NCR,505) FLABEL
62      WRITE(NPR,505) FLABEL
63      READ(NCR,10) (Y1VALS(I),I=1,ND)
64      READ(NCR,10) (Y6VALS(I),I=1,ND)
65      C..
66      C.
67      READ(NCR,505) FLABEL
68      WRITE(NPR,505) FLABEL
69      READ(NCR,10) (Y2VALS(I),Y7VALS(I),Y3VALS(I),Y4VALS(I),Y5VALS(I)
70      1,I=1,ND)
71      LSUM=0.0
72      DO 40 J=2,ND
73      40  LSUM=LSUM+Y5VALS(J)
74      LBAR=LSUM/(FLOAT(ND)-1.0)
75      DO 50 J=1,ND
76      Y7VALS(J)=Y2VALS(J)*Y7VALS(J)/LBAR
77      50  Y5VALS(J)=Y5VALS(J)/LBAR
78      C..
79      DO 20 I=1,ND
80      20  Y3VALS(I)=Y3VALS(I)/50.0
81      C..
82      C..  INSERT OTHERS IF REQUIRED
83      C
84      C..  SIZE THE VALUES
85      XVALS(ND+1)=SCALX1
86      XVALS(ND+2)=SCALX2
87      Y1VALS(ND+1)=SCALY1
88      Y1VALS(ND+2)=SCALY2
89      DO 310 N=1,2
90      Y2VALS(ND+N)=Y1VALS(ND+N)
91      Y3VALS(ND+N)=Y1VALS(ND+N)
92      Y4VALS(ND+N)=Y1VALS(ND+N)
93      Y5VALS(ND+N)=Y1VALS(ND+N)
94      Y6VALS(ND+N)=Y1VALS(ND+N)
95      310  Y7VALS(ND+N)=Y1VALS(ND+N)
96      C
97      C..  SET ORIGIN
98      XORIG=0.0
99      YORIG=0.0
100     CALL PLOT (XORIG,YORIG,-3)
101     WRITE(NPR,550)
102     550  FORMAT(' PLOT STARTED')
103     C..
104     C..  DRAW INNER FRAME
105     C
106     C      NAXIS(XST,YST,AXLEN,STARTING LOG OR 0 FOR LINEAR SCALE,
107     C      NO. OF LOGCYCS OR TICK INTVLs,ANG,CCW(1) OR CW(-1),
108     C      TICK LENGTH,LINE SOLID(2) OR BLANK(3) )
109     C
110     CALL NAXIS(0.,0.,YHIGH,0,16.,90.,-1,.25,2)
111     CALL NAXIS(0.,YHIGH,XLONG,0,8.,0.,-1,.25,2)
112     CALL NAXIS(0.,0.,XLONG,0,8.,0.,1,.25,2)
113     CALL NAXIS(XLONG,0.,YHIGH,0,16.,90.,1,.25,2)
114     CALL NAXIS(0.,7.,XLONG,0,8.,0.,-1,0.25,2)

```

```

115          CALL NAXIS(0.,7.,XLONG,0,8.,0.,1,0.25,3)
116          CALL NAXIS(0.,14.,XLONG,0,8.,0.,-1,0.25,2)
117          CALL NAXIS(0.,14.,XLONG,0,8.,0.,1,0.25,3)
118          CALL NAXIS(0.,21.,XLONG,0,8.,0.,-1,0.25,2)
119          CALL NAXIS(0.,21.,XLONG,0,8.,0.,1,0.25,3)
120      C
121          GO TO (160,150,140,130,120,110,100),KLINE$
122      100  CONTINUE
123          CALL NLINE(XVALS,Y3VALS,ND,1,0,0)
124      110  CONTINUE
125          CALL PLOT(0.,7.,-3)
126          CALL BRLINE(XVALS,Y5VALS,ND,SEGL1,2)
127      120  CONTINUE
128          CALL NLINE(XVALS,Y4VALS,ND,1,0,0)
129      130  CONTINUE
130          CALL PLOT(0.,7.,-3)
131          CALL BRLINE(XVALS,Y6VALS,ND,SEGL2,4)
132      140  CONTINUE
133          CALL NLINE(XVALS,Y7VALS,ND,1,0,0)
134      150  CONTINUE
135          CALL PLOT(0.,7.,-3)
136          CALL BRLINE(XVALS,Y1VALS,ND,SEGL2,4)
137      160  CONTINUE
138          CALL NLINE(XVALS,Y2VALS,ND,1,0,0)
139          CALL PLOT(0.,-21.,-3)
140      C
141          WRITE(NPR,560)
142      560  FORMAT(' ENTER ANNOTATIONS REQD, 4F5.2,15A4'/' OTHERWISE 999.')
143          CALL SCRIBE
144      C
145      C..  SIGN OFF
146          CALL PLOT (0,0,999)
147          WRITE(NPR,570)
148      570  FORMAT(' *PLOT DONE*')
149          STOP
150          END

```

APPENDIX D

CIRCUIT DIAGRAMS FOR GOUDKOPPIES APPLICATION

This Appendix presents diagrams for the various circuits required for interfacing the microcomputer and the equalization tank to implement the control strategy at the Goudkoppies WWTP. These diagrams, together with the additional information supplied on certain of the diagrams, provides a reference for the discussion in Section 3, Chapter 7 (Equipment Requirements for Implementation of Control Strategy).

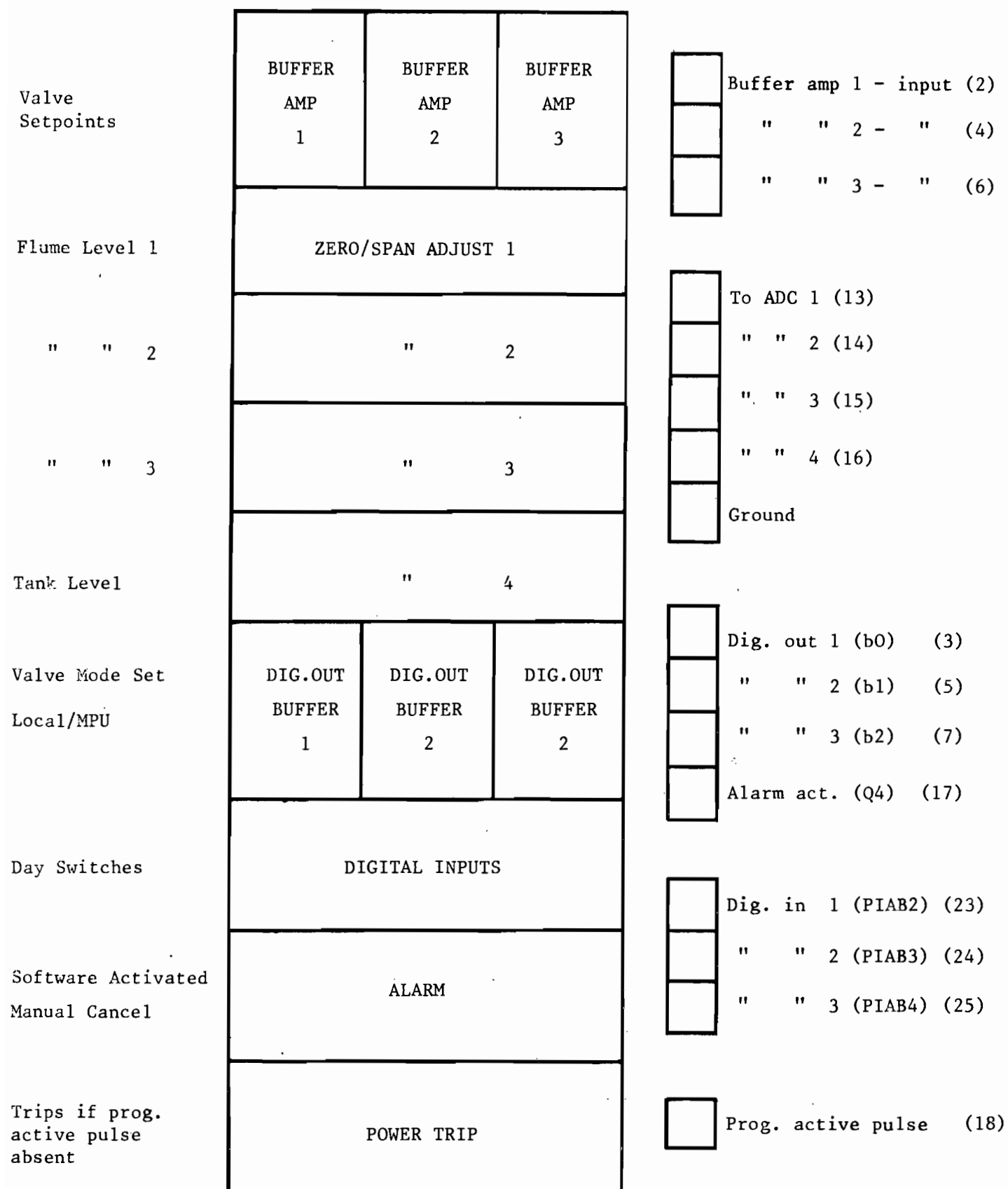


Fig D.1: Physical location of circuits on Interface Card.
(Numbers in brackets refer to pins on 25-way interface plug).

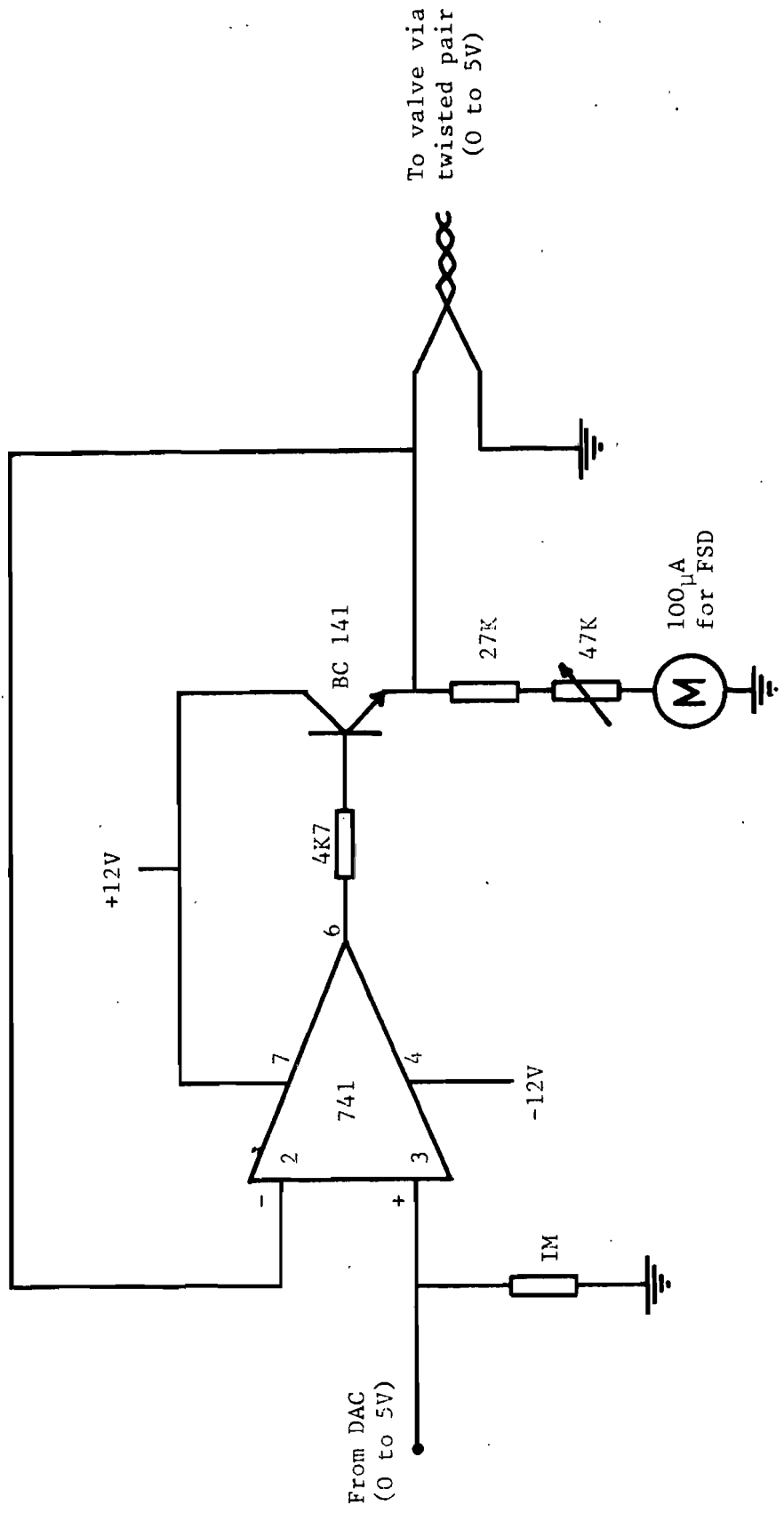


Fig D.2: Buffer Amplifier Circuit for valve setpoints.

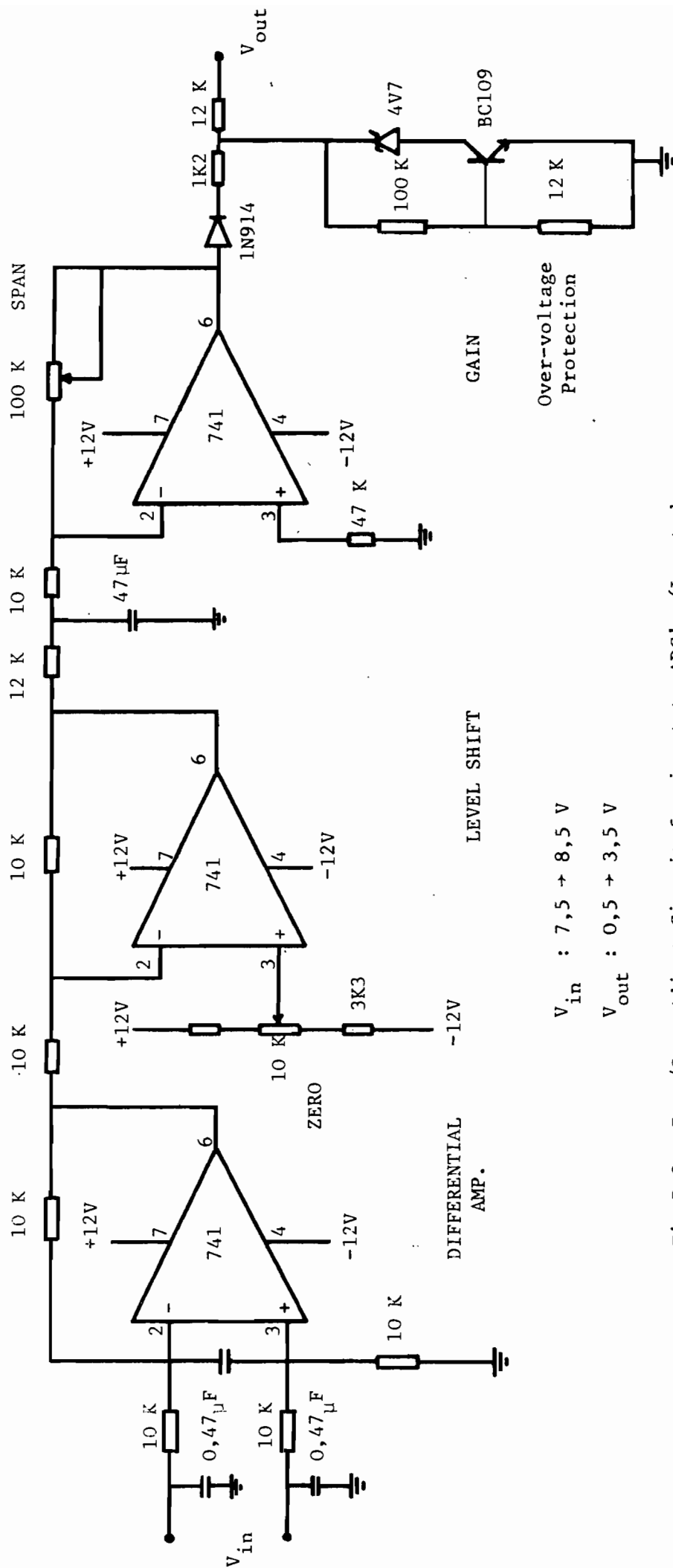


Fig D.3: Zero/Span Adjust Circuit for input to ADC's (Located in Interface Unit).

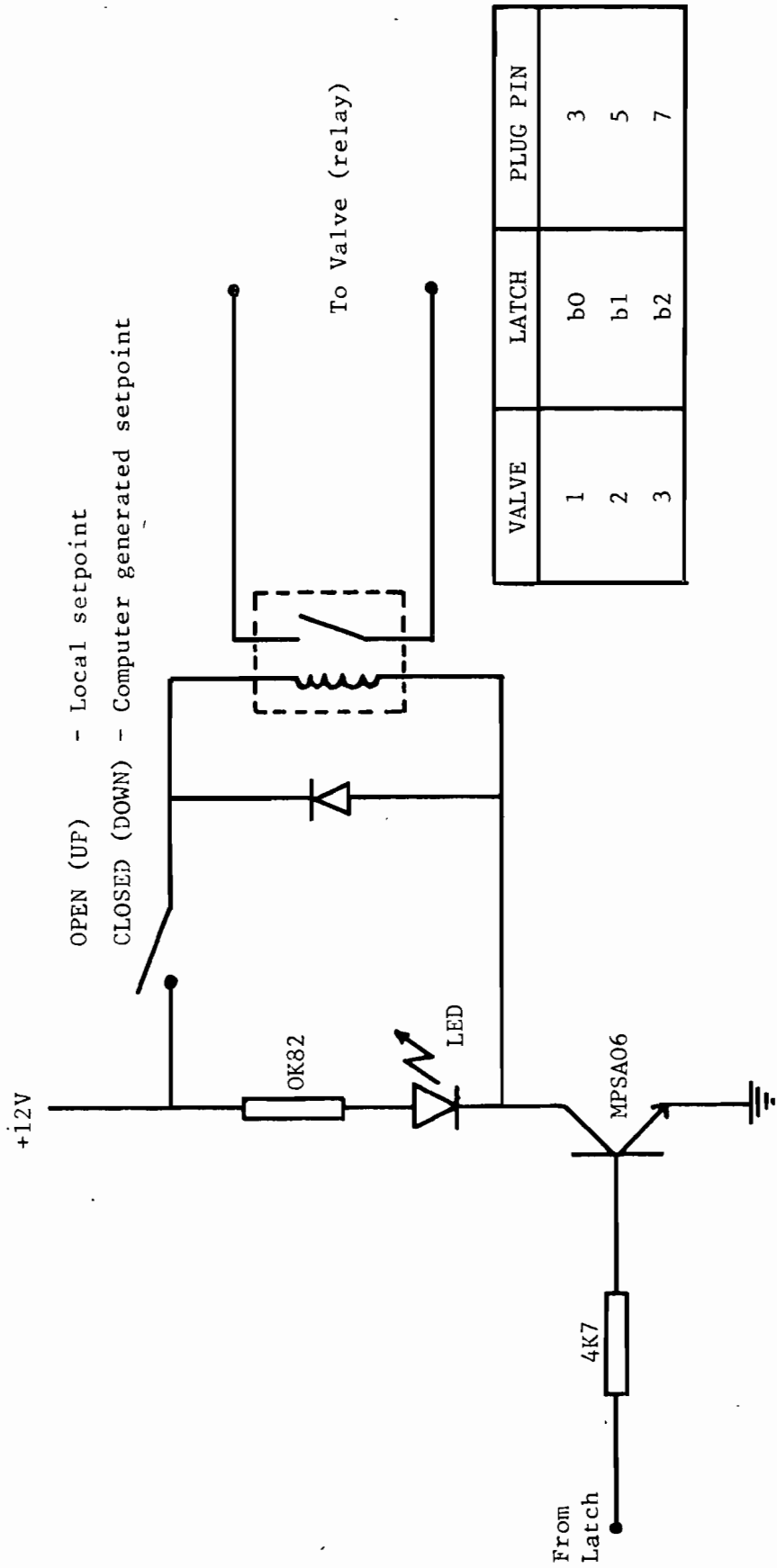


Fig D.4: Digital Output Circuit. Local/Computer control of valves controlled by digital output latch (on DAC card).

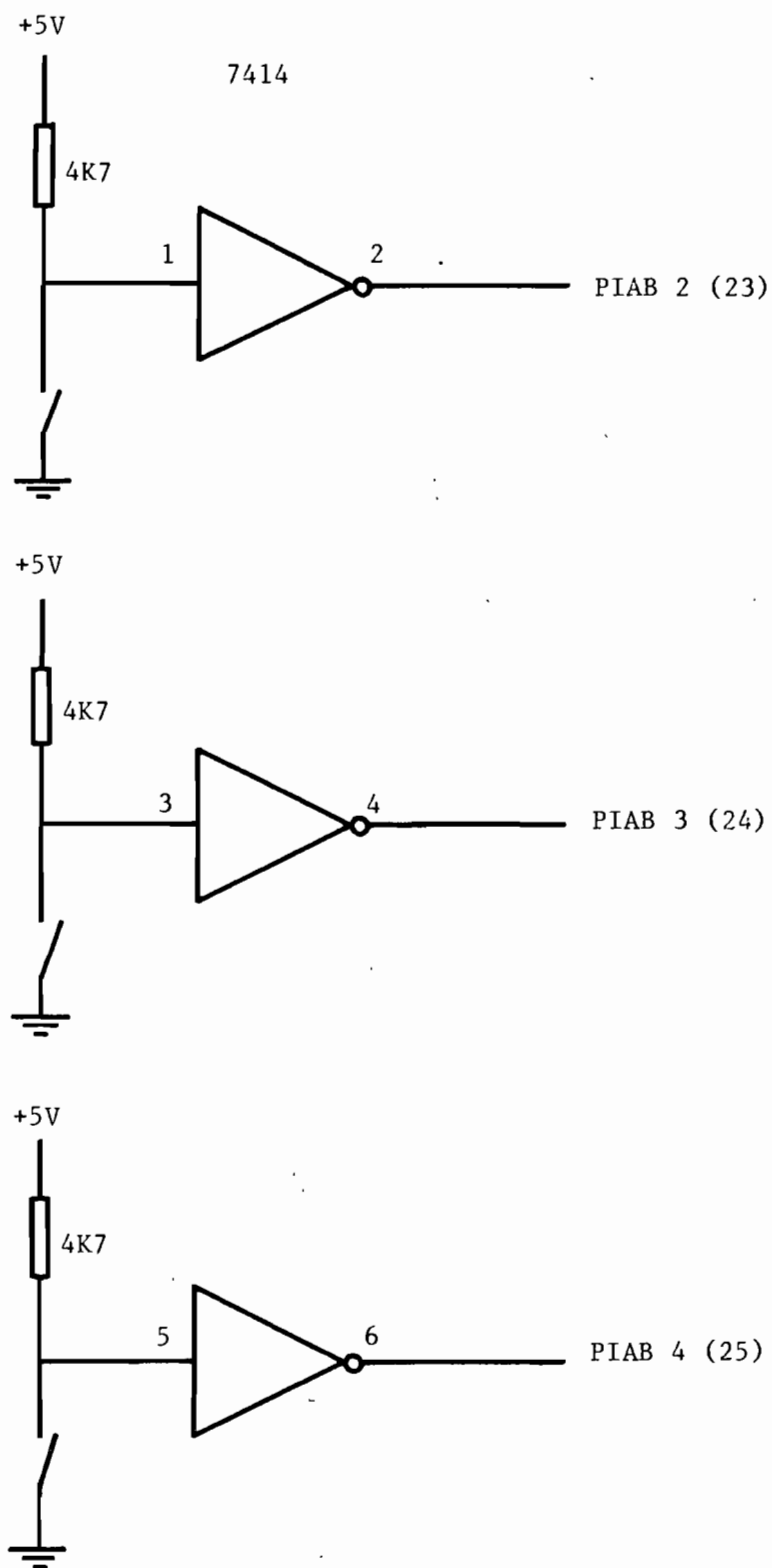


Fig D.5: Digital Inputs for Day Type Switches.
Switch closed is Read as Logical "1"
by the computer.

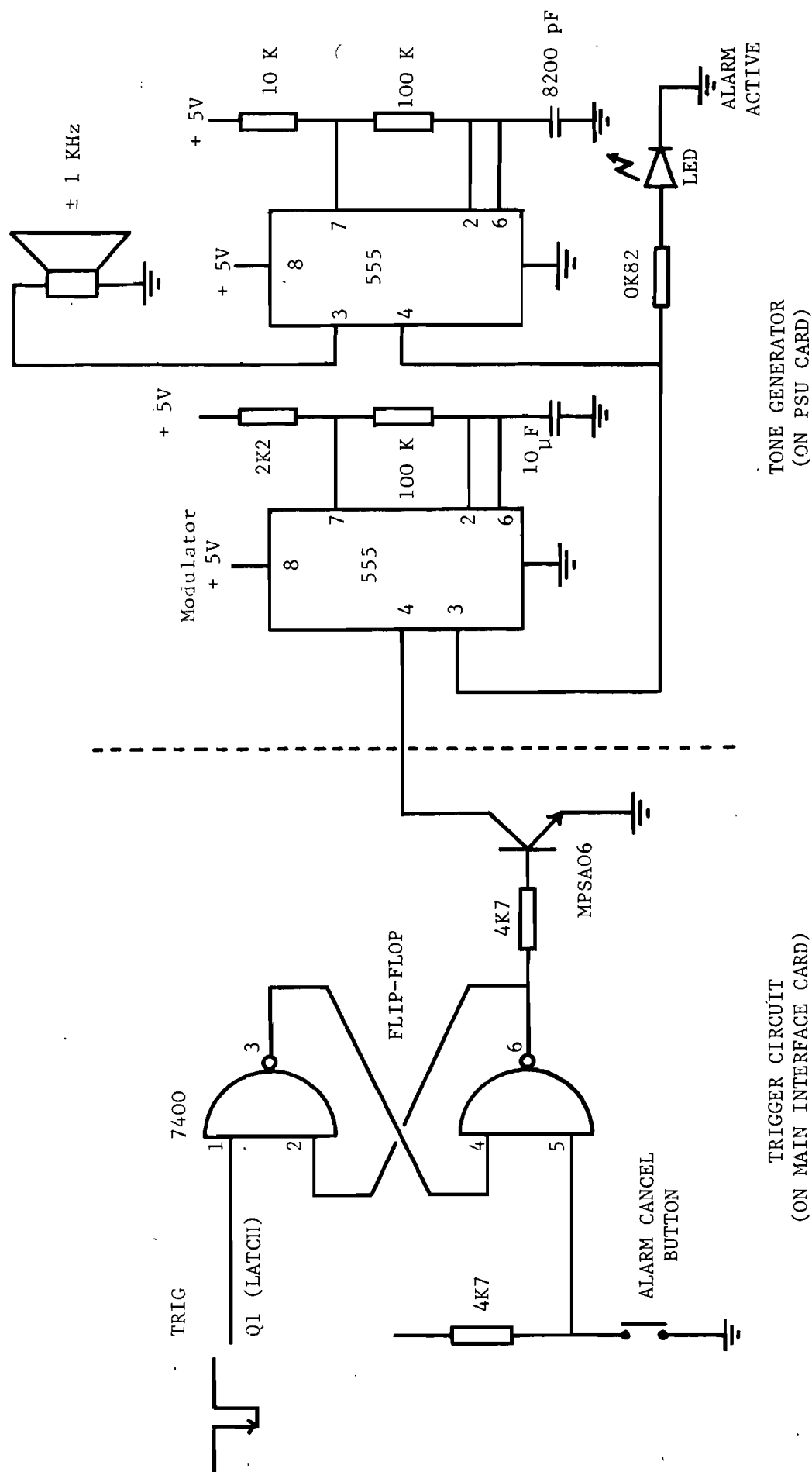


Fig D.6: Alarm Circuit Diagram.

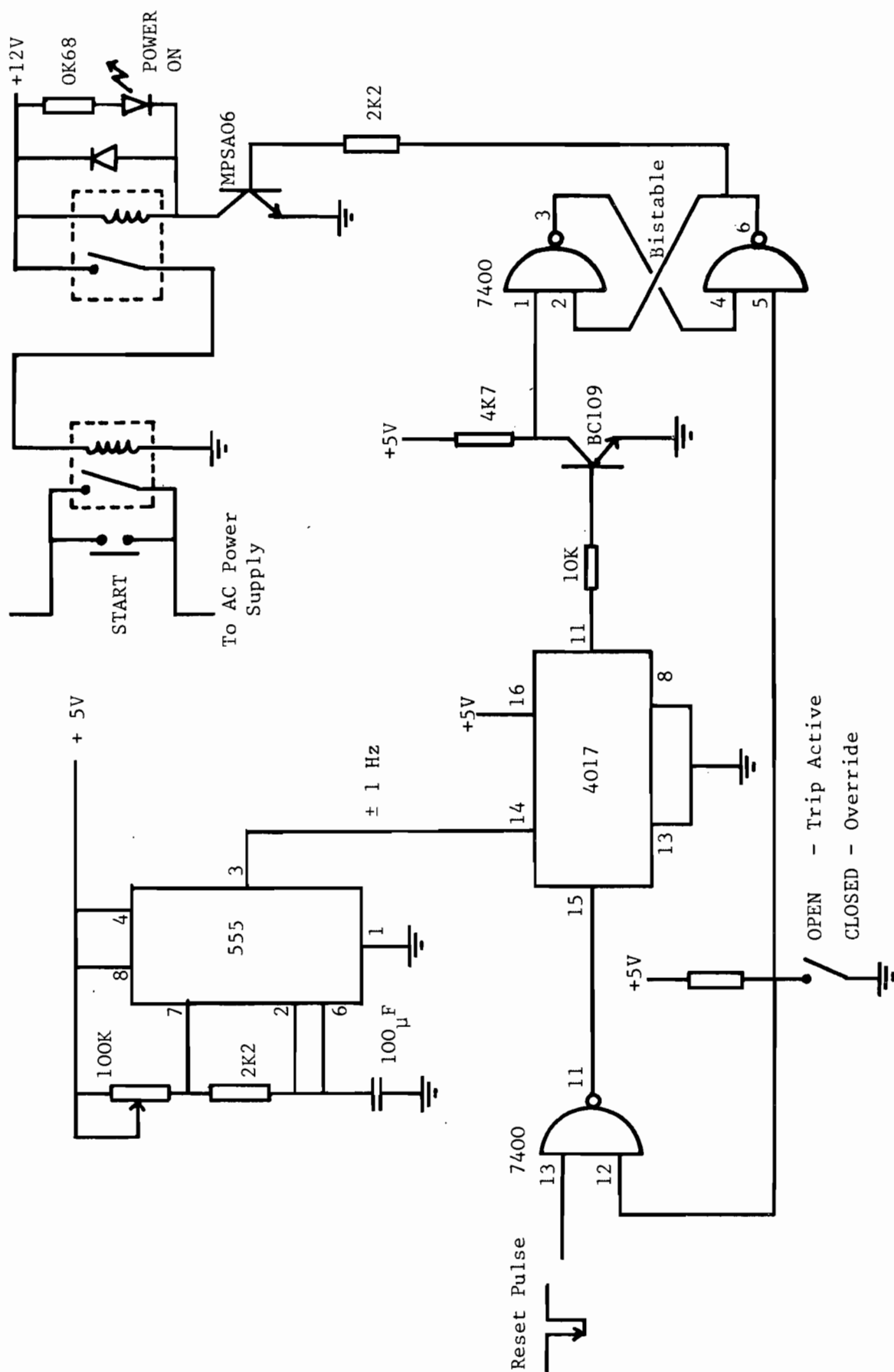


Fig D.7: Power Trip-out Circuit to trip in the absence of reset pulses from computer.

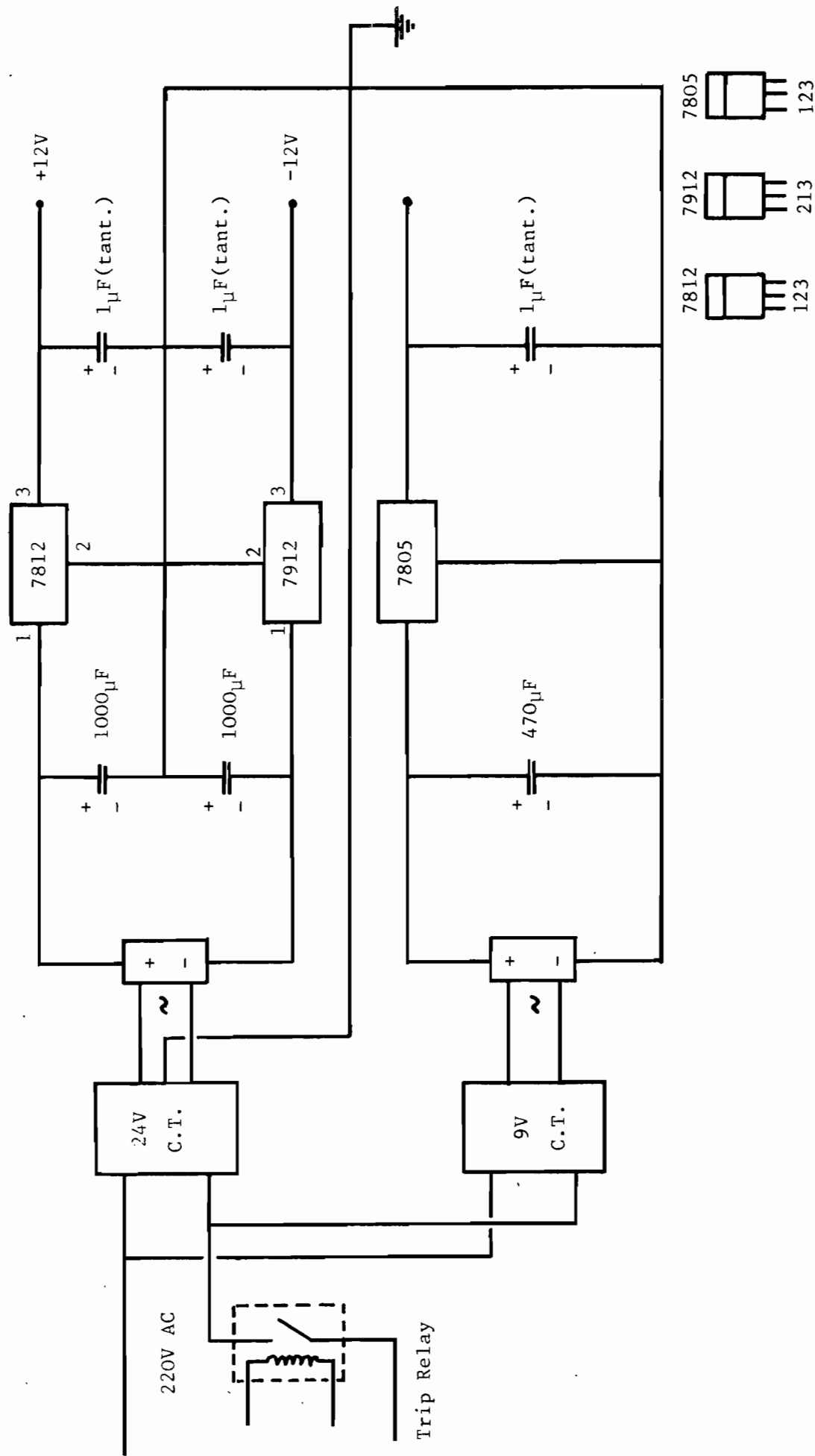


Fig D.8: Power Supplies for Interface Unit

TABLE D.1: PIA card I/O Functions (PIA is located in Port 7 of the SWTP microcomputer).

PIA side A : Outputs \$E070	bit 0 1 2 3 4 5 6 7	Ribbon cable to P2 on DAC/Clock card (Fig D.9). DAC's and Digital Outputs via Latches	
PIA side B : Inputs \$E072	bit 0 1 2 3 4 5 6 7	Clock LSB) Clock MSB) Day type switch 1 Day type switch 2 Day type switch 3 Spare Spare Spare	From P2 on DAC/Clock Card Pin 23 on interface plug " 24 " " " 25 " "
Latch PIA Card \$E07F	Q0 1 2 3 4 5 6 7	Program active pulse Alarm Not used Not used Strobe DAC 1 " 2 " 3 " dig.output latch	Pin 18 on interface plug " 17 " " To P2 on DAC/Clock Card
Digital Output Latch on DAC/Clock Card	bit 0 1 2 3-7	Setpoint for Valve 1 " " " " " " Spare	Pin 3 on interface plug " 5 " " " 7 " "

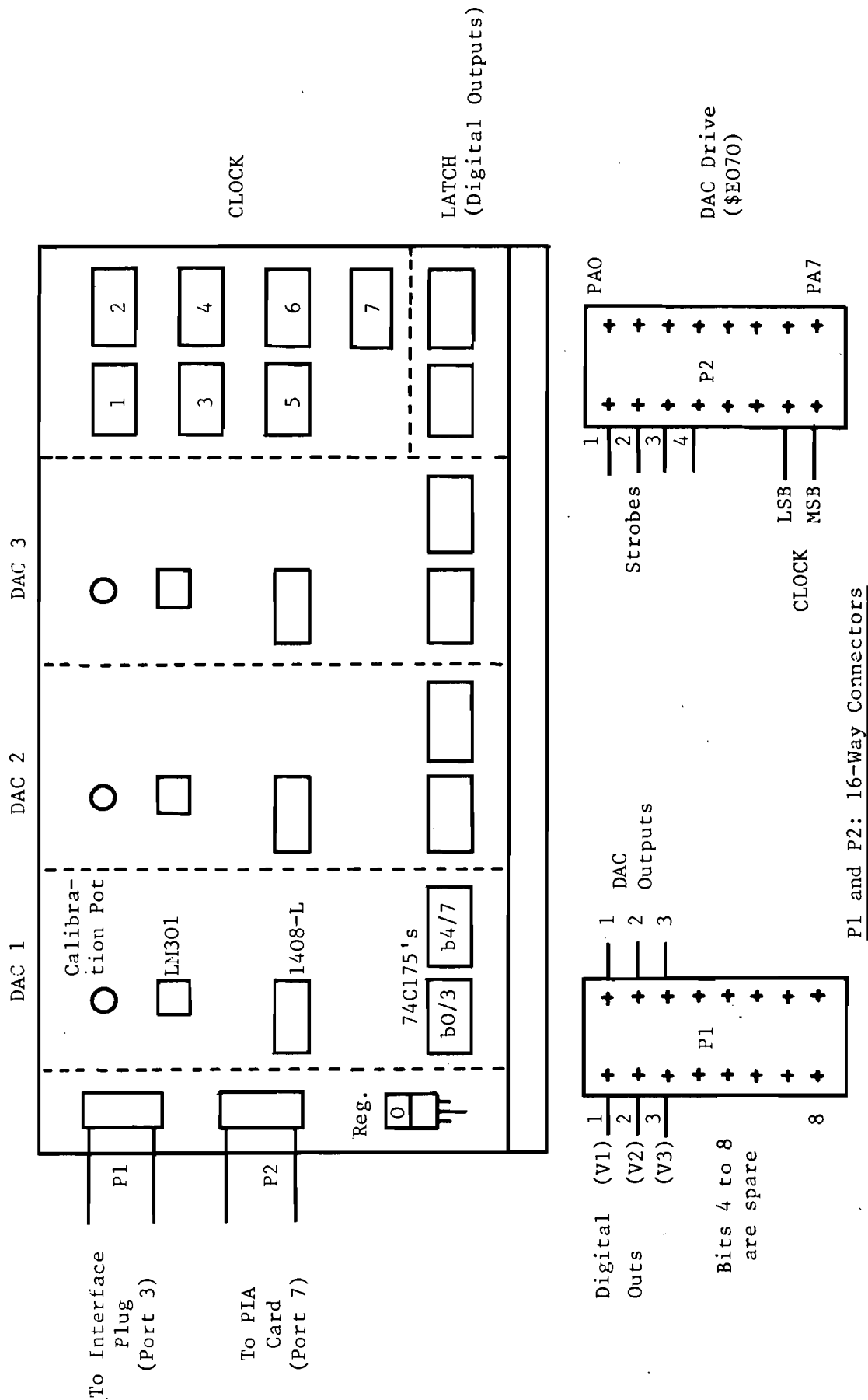
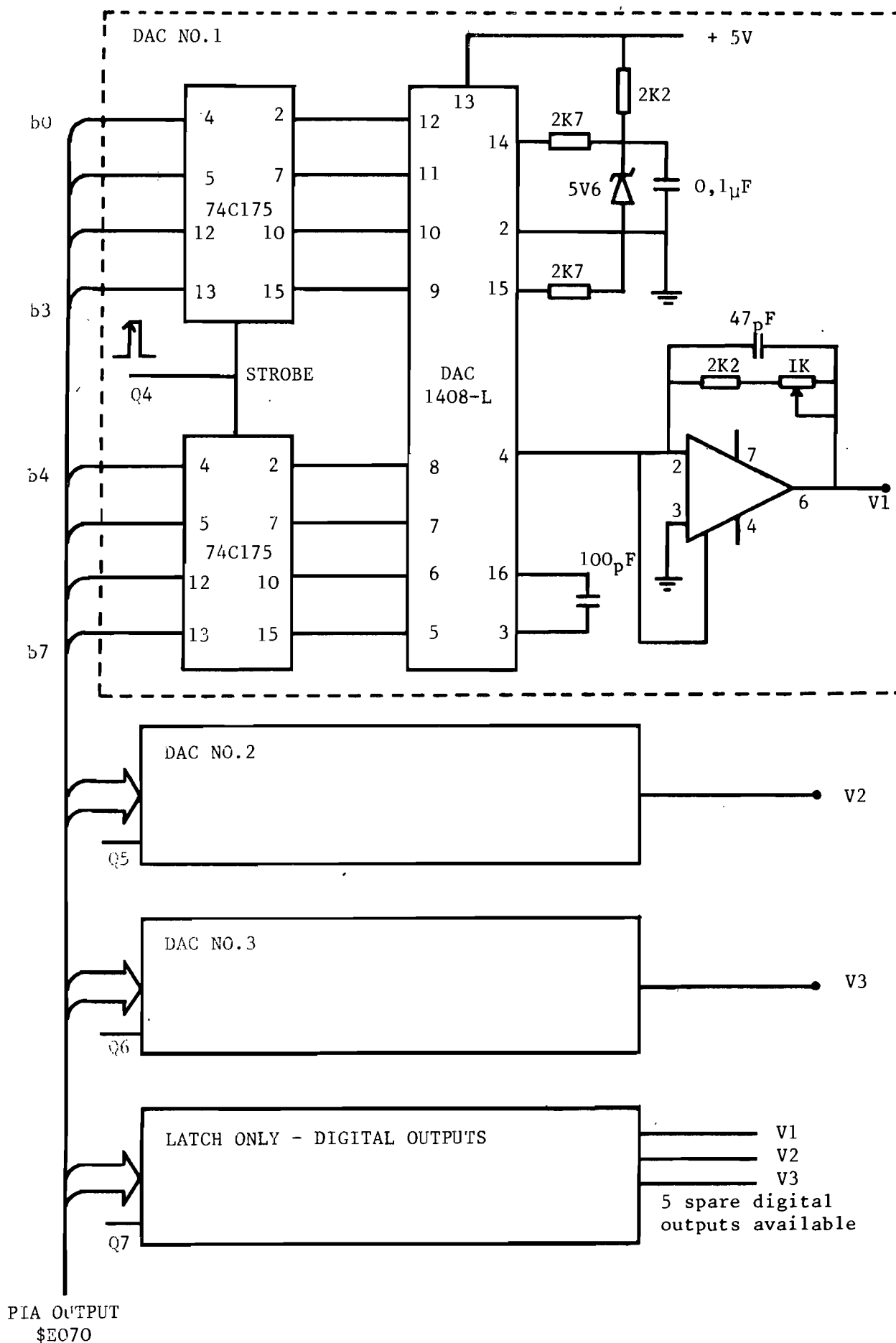


Fig D.9: Physical location of circuit sections on wire-wrap module
i.e. DAC's, Digital Output Latch, Clock.



PIA OUTPUT
\$EO70

Fig D.10: Digital to Analogue Converters and Latch for Digital Outputs. (Q4 to Q7 from latch on PIA card).

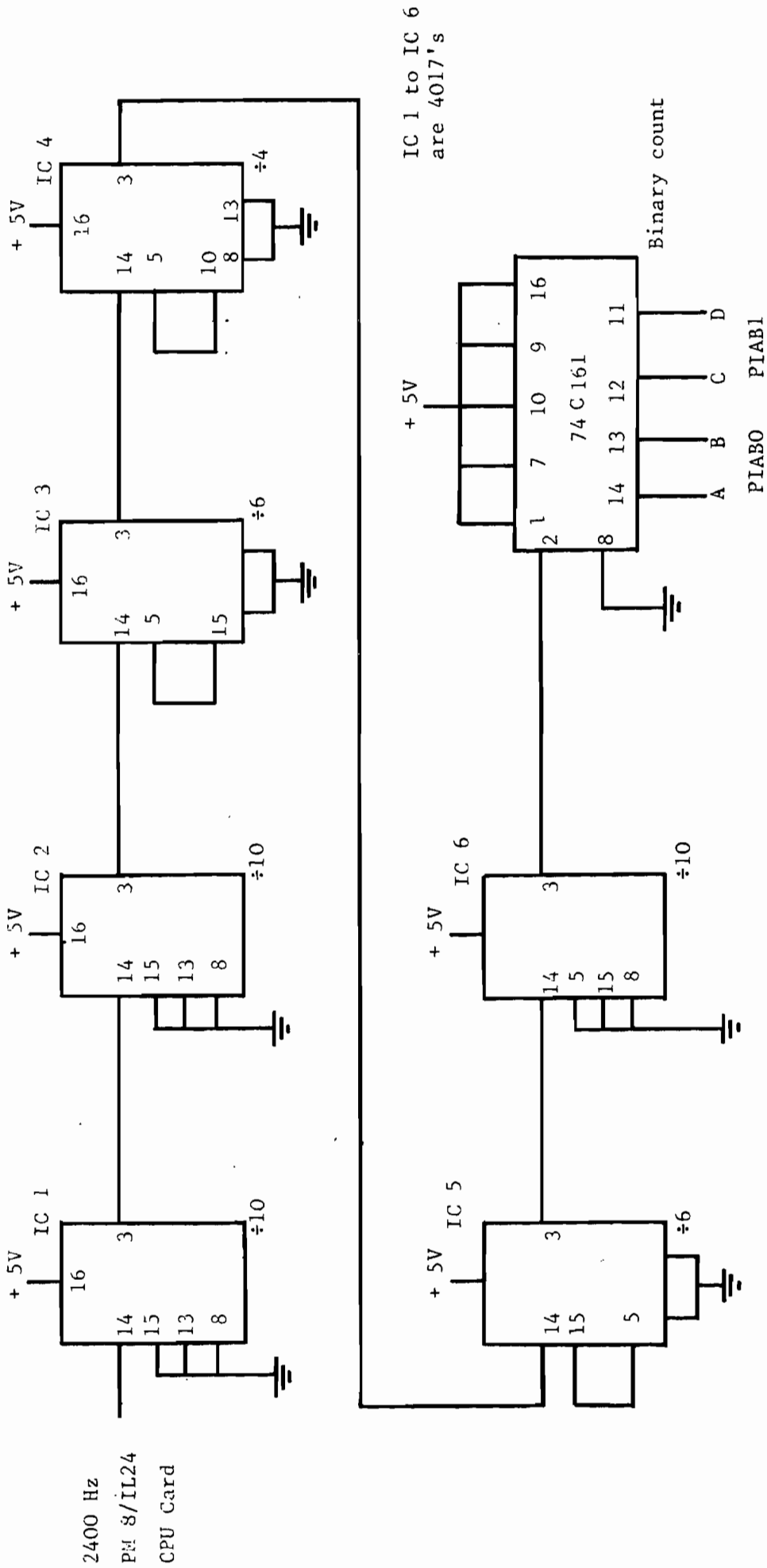


Fig D.11: Clock Circuit (on DAC Card). Division of 2400 Hz to give binary count of 1 count per minute.

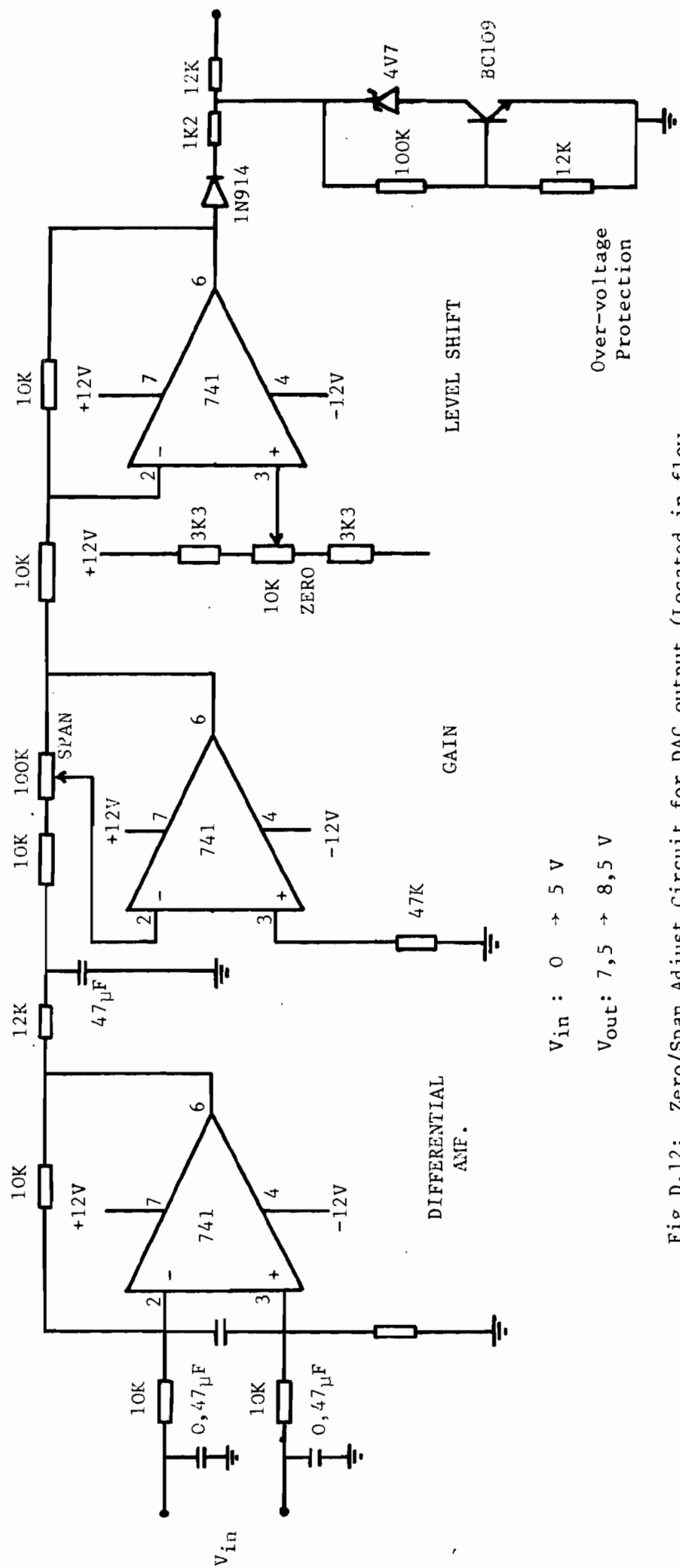


Fig D.12: Zero/Span Adjust Circuit for DAC output (Located in flow controller panels on plant).

A P P E N D I X E

REAL-TIME COMPUTER PROGRAMS - GOUDKOPPIES WWTP APPLICATION

Various details concerning the real-time microcomputer programs used in the implementation of the control strategy at the Goudkoppies plant are presented in this Appendix. This information supplies reference material for the detailed discussion of the structure and the specific functions of the different programs presented in Chapter 7; the information is divided into four sections:

- (1) Program listings
- (2) Documentation of operating procedures
- (3) Example of start-up procedure
- (4) Examples of output accessed during operation

E.1 Real-time Microcomputer Program Listings

Two microcomputer programs are required for implementation of the control strategy; these are

- (a) A mainline program called CONTROL which is written in the LUCIDATA version of the Pascal high level language.
- (b) A machine code program called MACHCD, consisting of a number of subprograms, which is written using the FLEX Mnemonic Assembler package.

```
+++RUN FASCAL CONTROL,,,1.CONTROL.SCR
```

```
P-6800  RUN-TIME  SYSTEM  V 2.9      : COPYRIGHT C 1980 LUCIDATA
USABLE CONTIGUOUS MEMORY $8000
DEFAULT STACK RESERVATION $1000
ENTER NEW VALUE OR RETURN $
```

PASCAL P-COMPILE (VERSION 2) : COPYRIGHT C 1980 D.R.GIBBY

```

0 PROGRAM CONTROL(FHST1,FHST2);
0 LABEL 1;
0 CONST
0 NINTPHR=2;
0 VOLUME=22.75;
0 TOPLIM=95.0;
0 BETA=2.0E-06;
0 ZETA=25.0;
0 LIMIT=0.02;
0 VAR
0 FINHST :ARRAY(1..2,1..48) OF REAL;
0 FEXIT,FOUT,FOUTT,FINEXP :ARRAY(1..48) OF REAL;
0 FINOLD,PCVOLD :ARRAY(1..48) OF REAL;
0 FEXOLD :ARRAY(1..3,1..48) OF REAL;
0 E :ARRAY(1..49) OF REAL;
0 PCVC,PCVCT :ARRAY(1..49) OF REAL;
0 FLOW :ARRAY(0..3) OF REAL;
0 FLOWACT :ARRAY(1..3) OF REAL;
0 SIGN :ARRAY(1..48) OF INTEGER;
0 FLOWINT :ARRAY(1..3) OF INTEGER;
0 FHST1,FHST2 :FILE OF REAL;
0
0 I,J,K,IC,ICLAST,JC,INITL,JCYC,
0 JYEST,JTODAY,JTOMOR,JNEXT,FLGOPT,
0 ITIME,TIMEH,TIMEM,HOURS,MINS,COPIES,
0 LAST,LASTM1,MINNEW,MINOLD,STARTUP,
0 ICHFLG,ADJUST,INTLEN,PRKT,IDUM,
0 FLAG1,FLAG2,FLAG3,FLAG4,FLAG5,
0 FLAG6,FLAG7,FLAG8,FLAG9,FLAG10,
0 FLAG11,FLAG12,FLAG13,FLAG14,
0 FLAGER,MANUAL,IPREV,DAY,SUBS :INTEGER;
0 THY,TDPM5,BOTPM5,AMULT,
0 DTC,DTCOA,DELFCT,CORRN,FOUTA,
0 FSUM,FSUM1,FBAR,FBAR1,
0 FINAM,PCVNOW,PCVLST,CHANGE,DELP,
0 F1,F2,CUMV,PCV,BOTLIM,
0 EFLOW,ELIM,EDIF,ERROR,
0 SEFLOW,SELIM,SEDIF,
0 TOTFLOW,NUMBER,
0 FPRV,P,Q,R,PCVSTRT,DIF :REAL;
0 CHSET :CHAR;
0
0
0
0
0 PROCEDURE PRTOPT; (* LIST POSSIBLE INTRPT. OPTIONS *)
0 BEGIN

```

```

4      WRITELN;WRITELN;
12     WRITELN("LIST OF INTERRUPT OPTIONS");
48     WRITELN("-----");WRITELN;
88     WRITELN("  OPT. NO.          ACTION");
124    WRITELN("  -----          -----");
160    WRITELN("      1          PRINT INPUT DATA");
200    WRITELN("      2          PRINT HISTORICAL INFLOW DATA");
252    WRITELN("      4          PRINT EXPECTED RESULTS FOR NEXT 24 HOURS");
316    WRITELN("      5          PRINT LEVEL SENSOR READING");
368    WRITELN("      6          PRINT CURRENT ERROR EXPRESSION VALUES");
428    WRITELN("      7          COMPARE ACTUAL AND REQUESTED OUTFLOWS");
488    WRITELN("      8          CHECK AND/OR CHANGE TIME OF DAY");
544    IF MANUAL>0 THEN
556      WRITELN("      9          CHECK AND/OR CHANGE FLOW TO MOD.",
600      MANUAL:2);
620    WRITELN;WRITELN;WRITELN;
632    POKE($7843,$95);
652    IDUM:=USER(0);          (* ENABLE INTERRUPT *)
668    POKE($7842,0);
688    POKE($7800,0)          (* FLGOPT=0 *)
704  END;
712
712
712
712
712  PROCEDURE PRINT1;          (* INPUT DATA *)
712  BEGIN
712    WRITELN;WRITELN;
720    WRITELN("*****");
752    WRITELN("  PROCESS INFORMATION");
784    WRITELN("*****");
816    WRITELN;
820    WRITELN("MEAN TANK RETENTION TIME (HOURS) =",THT:5:2);
872    WRITELN;
876    WRITELN("TANK HOLD-UP LIMITS (%):");
912    WRITELN("  ::10,"MAXIMUM =",TOPLIM:5:1);
952    WRITELN("  ::10,"MINIMUM =",BOTLIM:5:1);
988    WRITELN;
992    WRITELN("ERROR EXPRESSION WEIGHTING FACTORS :");
1040   WRITELN("  ::10,"BETA  =",BETA:10);
1080   WRITELN("  ::10,"ZETA  =",ZETA:4:1);
1120   WRITELN;
1124   WRITELN("MINIMUM FLOW INCREMENT =",LIMIT:5:2);
1172   WRITELN;WRITELN;WRITELN;
1184   POKE($7843,$95);
1204   IDUM:=USER(0);          (* ENABLE INTERRUPT *)
1220   POKE($7842,0);
1240   POKE($7801,0)          (* FLAG1=0 *)
1256  END;
1264
1264
1264
1264
1264  PROCEDURE PRINT2;          (* HISTORICAL DATA *)
1264  LABEL 2;
1264  BEGIN
1264    IF PRKT=0 THEN

```

```

1276 BEGIN
1276   WRITELN;WRITELN;
1284   WRITELN("*****");
1312   WRITELN(" HISTORICAL DATA");
1340   WRITELN("*****");
1368   WRITELN;
1372   WRITELN("  :13,"INFLOW RATE DATA");
1408   WRITELN("  :5,"TIME", "  :5,"(AVERAGE,L/S)");
1460   WRITELN("  :12,"WEEKDAY", "  :4,"WEEKEND");
1512   WRITELN;
1516   HOURS:=0;
1524   MINS:=0
1528   END;
1532 2:
1532   PRKT:=PRKT+1;
1544   F1:=FINHSTC1,PRKT)*FBAR;
1572   F2:=FINHSTC2,PRKT)*FBAR;
1600   IF MINS>9
1608     THEN WRITELN(HOURS:6,"H",MINS:2,F1:8:0,F2:11:0)
1652     ELSE WRITELN(HOURS:6,"H0",MINS:1,F1:8:0,F2:11:0);
1704   MINS:=MINS+INTLEN;
1720   IF MINS=60 THEN
1732     BEGIN
1732       HOURS:=HOURS+1;
1744       MINS:=0
1748     END;
1752   IF HOURS=24 THEN
1764     BEGIN
1764       WRITELN;WRITELN;WRITELN;
1776       PRKT:=0;
1784       POKE($7843,$95);
1804       IDUM:=USER(0);           (* ENABLE INTERRUPT *)
1820       POKE($7842,0);
1840       POKE($7802,0)           (* FLAG2=0 *)
1856     END;
1860   IF (PRKT MOD 5<>0) THEN GOTO 2
1876 END;
1884
1884
1884
1884
1884 PROCEDURE PRINT3;           (* ACT. RESULTS FOR LAST 24 HRS. *)
1884 LABEL 3;
1884 BEGIN
1884   IF PRKT=0 THEN
1896     BEGIN
1896       WRITELN;WRITELN;
1904       WRITELN("*****");
1948       WRITELN(" ACTUAL RESULTS FOR LAST 24 HOURS");
1992       WRITELN("*****");
2036       WRITELN;
2040       WRITELN("  :4,"TIME", "  :4,"INFLOW", "  :13,"OUTFLOW", "  :13,
2112         "HOLDUP");
2128       WRITELN("  :14,"L/S", "  :16,"L/S", "  :16,"(%)");
2192       WRITELN("  :25,"MOD.1 MOD.2 MOD.3");
2232       WRITELN;
2236       IDUM:=USER(1);

```

```

2252     HOURS:=8 ; MINS:=0;
2268     END;
2268 3:
2268     PRKT:=PRKT+1;
2280     SUBS:=HOURS*NINTPHR+MINS DIV INTLEN+1;
2312     F1:=FINOLDESUBS]*FBAR;
2336     IF MINS>9
2344         THEN WRITELN(HOURS:5,"H",MINS:2,F1:9:0,FEXOLDE1,SUBS]:12:0,
2400             FEXOLDE2,SUBS]:7:0,FEXOLDE3,SUBS]:7:0,PCVOLDESUBS]:13:1)
2456         ELSE WRITELN(HOURS:5,"H0",MINS:1,F1:9:0,FEXOLDE1,SUBS]:12:0,
2516             FEXOLDE2,SUBS]:7:0,FEXOLDE3,SUBS]:7:0,PCVOLDESUBS]:13:1);
2576     MINS:=MINS+INTLEN;
2592     IF MINS=60 THEN
2604         BEGIN
2604             HOURS:=HOURS+1;
2616             MINS:=0
2620         END;
2624     IF HOURS=24 THEN HOURS:=0;
2644     IF PRKT=LASTM1 THEN
2656         BEGIN
2656             WRITELN;WRITELN;WRITELN;WRITELN;
2672             PRKT:=0;
2680             COPIES:=COPIES+1;
2692             IF COPIES=2 THEN
2704                 BEGIN
2704                     COPIES:=0;
2712                     FLAG3:=0;
2720                     END;
2720             END;
2720     IF (PRKT MOD 5<>0) THEN GOTO 3
2736     END;
2744
2744
2744
2744
2744 PROCEDURE PRINT4; . (* OPT. RESULTS FOR NEXT 24 HRS. *)
2744 LABEL 4;
2744 BEGIN
2744     IF PRKT=0 THEN
2756         BEGIN
2756             WRITELN;WRITELN;
2764             WRITELN("*****");
2812             WRITELN(" OPTIMUM RESULTS FOR NEXT 24 HOURS");
2856             WRITELN("*****");
2904             WRITELN;
2908             WRITELN("  ::11,"EXPECTED    OPTIMUM", "  ::3,"EXPECTED");
2968             WRITELN("  ::4,"TIME", "  ::4,"INFLOW", "  ::4,"
3016                 "OUTFLOW    HOLDUP");
3044             WRITELN("  ::14,"L/S", "  ::7,"L/S", "  ::7,"(%)");
3108             WRITELN;
3112             HOURS:=ITIME DIV NINTPHR;
3124             IF NINTPHR=1
3132                 THEN MINS:=0
3140                 ELSE MINS:=(ITIME MOD NINTPHR)*INTLEN
3156             END;
3168 4:
3168     PRKT:=PRKT+1;

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```

3180 F1:=FINEXC[PRKT]*FBAR;
3204 F2:=FOUTC[PRKT]*FBAR;
3228 IF MINS>9
3236 THEN WRITELN(HOURS:5,"H",MINS:2,F1:9:0,
3272 F2:10:0,PCVCE[PRKT]:11:1)
3296 ELSE WRITELN(HOURS:5,"H0",MINS:1,F1:9:0,
3336 F2:10:0,PCVCE[PRKT]:11:1);
3364 MINS:=MINS+INTLEN;
3380 IF MINS=60 THEN
3392 BEGIN
3392 HOURS:=HOURS+1;
3404 MINS:=0
3408 END;
3412 IF HOURS=24 THEN HOURS:=0;
3432 IF PRKT=LASTM1 THEN
3444 BEGIN
3444 PRKT:=PRKT+1;
3456 IF MINS>9
3464 THEN WRITELN(HOURS:5,"H",MINS:2," ":5," --- ",
3512 " ":5," --- ",PCVCE[PRKT]:10:1)
3548 ELSE WRITELN(HOURS:5,"H0",MINS:1," ":5," --- ",
3600 " ":5," --- ",PCVCE[PRKT]:10:1);
3640 WRITELN;WRITELN;WRITELN;
3652 PRKT:=0;
3660 POKE($7843,$95);
3680 IDUM:=USER(0); (* ENABLE INTERRUPT *)
3696 POKE($7842,0);
3716 POKE($7804,0) (* FLAG4=0 *)
3732 END;
3736 IF (PRKT MOD 5<>0) THEN GOTO 4
3752 END;
3760
3760
3760
3760
3760 PROCEDURE PRINT5; (* LEVEL SENSOR READING *)
3760 BEGIN
3760 WRITELN;WRITELN;
3768 WRITELN(" LEVEL SENSOR READING:");
3804 IDUM:=USER(5);
3820 F1:=22.0+PEEK($7813)*78.0/255;
3872 WRITELN(" HOLD-UP =",F1:5:1,"%");
3916 WRITELN;WRITELN;
3924 POKE($7843,$95);
3944 IDUM:=USER(0); (* ENABLE INTERRUPT *)
3960 POKE($7842,0);
3980 POKE($7805,0) (* FLAG5=0 *)
3996 END;
4004
4004
4004
4004 PROCEDURE PRINT6; (* PRESENT ERROR DISTRIBUTION *)
4004 BEGIN
4004 WRITELN;WRITELN;
4012 WRITELN(" PRESENT ERROR DISTRIBUTION:");
4052 WRITELN(" -----");

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4092  WRITELN;
4096  WRITELN("  :6,"FLOW  = ",EFLOW:6:4);
4132  WRITELN("  :6,"LIMIT = ",ELIM:6:4);
4168  WRITELN("  :6,"DF/DT = ",EDIF:6:4);
4204  WRITELN("  :14,"-----");
4228  WRITELN("  :6,"TOTAL = ",ERROR:6:4);
4264  WRITELN;WRITELN;
4272  WRITELN("    CYCLE NO.  =",JCYC:3);
4308  WRITELN("    CALC. INT.  =",IC:3);
4344  WRITELN("    NO. ADJUSTMENTS IN PRESENT CYCLE =",ICHFLG:3);
4400  WRITELN;WRITELN;
4408  POKE($7843,$95);
4428  IDUM:=USER(0);          (* ENABLE INTERRUPT *)
4444  POKE($7842,0);
4464  POKE($7806,0);          (* FLAG6=0 *)
4480  END;
4488
4488
4488
4488
4488  PROCEDURE PRINT7;          (* ACTUAL AND REQUESTED OUTFLOW RATES *)
4488
4488  FUNCTION SQROOT(VALUE:REAL):REAL;
4492  VAR
4492  ROOT    :REAL;
4492  BEGIN
4496  IF VALUE<1
4504  THEN SQROOT:=0
4512  ELSE
4524  BEGIN
4524  ROOT:=1;
4536  REPEAT
4536  ROOT:=(VALUE/ROOT+ROOT)/2
4560  UNTIL ABS(VALUE/SQR(ROOT)-1)<1E-06;
4608  SQROOT:=ROOT;
4616  END;
4616  END;
4620
4620  BEGIN
4620  WRITELN;WRITELN;
4628  WRITELN("  :12,"OUTFLOW RATES (L/S)");
4668  WRITELN("MODULE      REQUESTED  ACTUAL");
4708  WRITELN("-----      -");
4748  IDUM:=USER(5);
4764  FLOWACTE1J:=PEEK($7810)/3.2345;
4804  FLOWACTE2J:=PEEK($7811)/3.2345;
4844  FLOWACTE3J:=PEEK($7812)/3.2345;
4884  FOR I:=1 TO 3 DO
4896  BEGIN
4904  NUMBER:=FLOWACTE1J*SQR(FLOWACTE1J);
4940  FLOWACTE1J:=SQROOT(NUMBER)+20;
4972  WRITELN(I:3,FLOWE1J:16:0,FLOWACTE1J:10:0);
5016  END;
5036  WRITELN;WRITELN;
5044  POKE($7843,$95);
5064  IDUM:=USER(0);          (* ENABLE INTERRUPT *)
5080  POKE($7842,0);

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```

5100   POKE($7807,0)                (* FLAG7=0 *)
5116   END;
5124
5124
5124
5124
5124
5124   PROCEDURE INITIAL;              (* CALC. INIT. AT 30 MIN INTERVAL *)
5124   BEGIN
5124     IF INITL<2
5132     THEN
5136       BEGIN
5136         DELFCT:=0;
5148         INITL:=INITL+1
5156       END
5160     ELSE
5164       BEGIN
5164         IF ITIME=1
5172         THEN
5176           BEGIN
5176             IPREV:=LASTM1;
5184             DAY:=JYEST
5184           END
5192         ELSE
5196           BEGIN
5196             IPREV:=ITIME-1;
5208             DAY:=JTODAY
5208           END;
5216         FINAM:=FEXITCIPREVJ+(PCVSTRT-PCVLST)/DTCOA;
5256         FINOLDCIPREVJ:=FINAM;
5272         PCVOLDCIPREVJ:=PCVLST;
5288         TOTFLOW:=FEXITCIPREVJ*FBAR-FLOWCMANUALJ;
5328         IF MANUAL=0 THEN TOTFLOW:=TOTFLOW/3
5348             ELSE TOTFLOW:=TOTFLOW/2;
5376         FOR I:=1 TO 3 DO
5388           IF I=MANUAL THEN FEXOLDCI,IPREVJ:=FLOWCMANUALJ
5428             ELSE FEXOLDCI,IPREVJ:=TOTFLOW;
5480         DELFCT:=0.4*DELFCT+0.6*(FINAM-FINHSTCDAY,IPREVJ);
5540         FINHSTCDAY,IPREVJ:=0.95*FINHSTCDAY,IPREVJ
5572             +0.05*FINAM
5588       END;
5604       CORRN:=DELFCT;
5612       PCVCCI:=PCVSTRT+DTCOA*(FINHSTCJTODAY,ITIMEJ+CORRN-FEXITCITIMEJ);
5680       PCVLST:=PCVSTRT;
5688       CORRN:=0.3*CORRN;
5708       IF ITIME<>LASTM1 THEN
5720         BEGIN
5720           FOR I:=ITIME+1 TO LASTM1 DO
5736             BEGIN
5744               FINEXPCI-ITIMEJ:=FINHSTCJTODAY,IJ+CORRN;
5788               CORRN:=0.3*CORRN;
5808               FOUTCI-ITIMEJ:=FEXITCIJ
5832             END
5840           END;
5860           FOR I:=1 TO ITIME DO
5872             BEGIN
5880               FINEXPCI-ITIME+LASTM1J:=FINHSTCJTOMOR,IJ+CORRN;
5932             CORRN:=0.3*CORRN;

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5952      FOUTCI-ITIME+LASTMIJ:=FEXITCIJ
5984      END;
6012      FSUM1:=0;          (* CALC MEAN INFLOW FOR NEXT 24 HOURS *)
6024      FOR I:=1 TO LASTM1 DO FSUM1:=FSUM1+FINEXPCIJ;
6088      FBAR1:=FSUM1/LASTM1;
6104      FOR I:=1 TO LASTM1 DO
6116          PCVCTCIJ:=PCVCTCIJ+DTCOA*(FINEXPCIJ-FOUTCIJ);
6212      FOR I:=1 TO LASTM1 DO          (* SET UP SCRATCH ARRAYS *)
6224          BEGIN
6232              PCVCTCIJ:=PCVCTCIJ;
6256              FOUTTCIJ:=FOUTCIJ
6272          END;
6300      PCVCTELASTJ:=PCVCTELASTJ;
6324      JCYC:=0;
6332      FLAG10:=0;
6340      FLAG11:=1
6344      END;
6352
6352
6352
6352
6352
6352 PROCEDURE OPTIMUM;          (* OPTIMIZATION CALC. *)
6352
6352 PROCEDURE ERCALC;
6356
6356 BEGIN
6356     IF IC=1
6364     THEN
6368         BEGIN
6368             K:=1;
6376             SEFLOW:=0;
6388             SELIM:=0;
6400             SEDIF:=0;
6412             ICLAST:=1
6416         END
6420     ELSE          (* IC>1 *)
6424         BEGIN
6424             IF IC<>ICLAST
6428                 THEN K:=IC-1
6444                 ELSE K:=IC
6452         END;
6460     IF K=1 THEN FPRV:=FEXITIITIMEJ
6480         ELSE FPRV:=FOUTTEK-1J;
6512     EFLOW:=SEFLOW;          (* CALC. ERROR VALUES *)
6520     ELIM:=SELIM;
6528     EDIF:=SEDIF;
6536     R:=0;
6548     FOR I:=K TO LASTM1 DO
6560         BEGIN
6568             P:=FOUTTCIJ/FBAR1-1;
6600             EFLOW:=EFLOW+P*P;
6624             IF FOUTTCIJ<>FPRV THEN
6644                 EDIF:=EDIF+(FOUTTCIJ-FPRV)*(FOUTTCIJ-FPRV);
6700             IF PCVCTCIJ>TOPM5 THEN R:=PCVCTCIJ-TOPM5;
6744             IF PCVCTCIJ<BOTP5 THEN R:=BOTP5-PCVCTCIJ;
6788             ELIM:=ELIM+R*R*R*R*R*R;

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```

6844     IF (I=K) AND (IC<>ICLAST) THEN
6872         BEGIN
6872             SEFLOW:=EFLOW;
6880             SELIM:=ELIM;
6888             SEDIF:=EDIF
6888         END;
6896         FPRV:=FOUTTCI;
6904     END;
6932     EFLOW:=EFLOW/LASTM1;
6948     ELIM:=BETA*ELIM/LASTM1;
6976     EDIF:=ZETA*EDIF/LASTM1;
7004     ERROR:=EFLOW+ELIM+EDIF;
7028     ICLAST:=IC
7028 END;
7040
7040
7040
7040 BEGIN          (* CONTENTS OF OPTIMUM *)
7040     IF JCYC=0 THEN          (* CALC. INITIAL ERROR VALUE *)
7052         BEGIN
7052             JCYC:=1;
7060             IC:=1;
7068             ERCALC;
7072             EC1J:=ERROR;
7088             ICHFLG:=0
7092         END;
7096         JC:=IC+1;
7108         CHANGE:=LIMIT*SIGNC1J;          (* CHANGE IN PREV. BEST DIR. *)
7136         FOUTTC1J:=FOUTTC1J+CHANGE;
7168         DELP:=-DTCOA*CHANGE;
7188         FOR I:=IC TO LASTM1 DO
7200             PCVCTEI+1J:=PCVCTEI+1J+DELP;
7268         ERCALC;
7272         ECJC1:=ERROR;
7288         IF ECJC1>EC1J THEN
7316             BEGIN          (* CHANGE IN OPPOSITE DIRECTION *)
7316                 SIGNC1J:=-SIGNC1J;
7344                 CHANGE:=LIMIT*SIGNC1J;
7372                 FOUTTC1J:=FOUTTC1J+CHANGE;
7404                 DELP:=-DTCOA*CHANGE;
7424                 FOR I:=IC TO LASTM1 DO
7436                     PCVCTEI+1J:=PCVCTEI+1J+DELP;
7504                 ERCALC;
7508                 ECJC1:=ERROR
7516             END;
7524             IF ECJC1<EC1J
7544             THEN
7552                 BEGIN
7552                     FOUTTC1J:=FOUTTC1J;
7576                     FOR I:=IC TO LASTM1 DO
7588                         PCVCTEI+1J:=PCVCTEI+1J;
7648                     ICHFLG:=ICHFLG+1;
7660                 END
7660             ELSE
7664                 BEGIN

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```

7664     ELCIC:=ELIC;
7688     FOUTLIC:=FOUTLIC;
7712     PCVCLIC+1:=PCVCLIC+1;
7736     END;
7744     IF (IC+ITIME)<LAST
7756     THEN FEXITLIC+ITIME:=FOUTLIC;
7788     ELSE FEXITLIC+ITIME-LASTM1:=FOUTLIC;
7840     IC:=IC+1;
7852     IF (IC=LAST) AND (ICHFLG)=4) THEN
7880     BEGIN
7880     IC:=1;
7888     JCYC:=JCYC+1;
7900     EL1:=ELLAST;
7924     ICHFLG:=0;
7928     END;
7932     IF (IC=LAST) AND (ICHFLG<4) THEN FLAG11:=0;
7968     END;
7972
7972
7972
7972
7972 PROCEDURE EMERGE;          (* EMERGENCY CONTROLLER *)
7972
7972 FUNCTION SQROOT(VALUE:REAL):REAL;
7976     VAR
7976     ROOT    :REAL;
7976     BEGIN
7980     IF VALUE<1
7988     THEN SQROOT:=0
7996     ELSE
8008     BEGIN
8008     ROOT:=1;
8020     REPEAT
8020     ROOT:=(VALUE/ROOT+ROOT)/2
8044     UNTIL ABS(VALUE/SQ(ROOT)-1)<1E-06;
8092     SQROOT:=ROOT;
8100     END;
8100     END;
8104
8104 BEGIN
8104     IF (PCVNOW<22) OR (PCVNOW>105) THEN FLAGER:=1;
8140     IF STARTUP=1 THEN
8152     BEGIN
8152     IDUM:=USER(5);
8168     FLOWACT1:=PEEK($7810)/3.2345;
8208     FLOWACT2:=PEEK($7811)/3.2345;
8248     FLOWACT3:=PEEK($7812)/3.2345;
8288     FOR I:=1 TO 3 DO
8300     BEGIN
8308     NUMBER:=FLOWACTI*SQ(RFLOWACTI);
8344     FLOWACTI:=SQROOT(NUMBER)+20;
8376     IF FLOWEII>0 THEN
8396     DIF:=(FLOWACTI-FLOWEII)/FLOWEII;
8444     IF ABS(DIF)>0.5 THEN FLAGER:=2;
8468     END;
8492     ADJUST:=0;          (* ADJUST SETPOINTS *)
8500     FOR I:=1 TO 3 DO

```

```

8512      BEGIN
8520      DIF:=FLOWE13-FLOWACTE13;
8552      IF (ABS(DIF)>15) AND (FLOWE13>0) THEN
8592      BEGIN
8592      ADJUST:=1;
8600      FLOWINTE13:=FLOWINTE13+ROUND(0.255*DIF);
8648      IF FLOWINTE13>255 THEN FLOWINTE13:=255;
8684      IF FLOWINTE13<0 THEN FLOWINTE13:=0;
8720      END;
8720      END;
8740      IF ADJUST=1 THEN
8752      BEGIN
8752      POKE($7821,FLOWINTE13);
8780      POKE($7822,FLOWINTE23);
8808      POKE($7823,FLOWINTE33);
8836      POKE($7824,$07);
8856      IDUM:=USER(6)          (* WRITE TO DAC'S *)
8864      END;
8872      END;
8872      IF FLAG8>0 THEN
8884      BEGIN
8884      POKE($7824,$00);
8904      IDUM:=USER(7);          (* SWITCH TO MANUAL *)
8920      Writeln;
8924      Writeln("THE SYSTEM REVERTED TO MANUAL CONTROL BECAUSE");
8980      IF FLAG8=1 THEN
8992      Writeln("THE LEVEL SENSOR IS NOT WORKING.");
9036      IF FLAG8=2 THEN
9048      Writeln("OF A DIFFERENCE BETWEEN ACTUAL & REQUESTED OUTFLOWS");
9112      Writeln(" * OFF-LINE TIME WAS ",TIMEH:2,"H",TIMEM:2);
9168      IDUM:=USER(2);          (* SET OFF ALARM *)
9184      FLAG10:=0;
9192      FLAG11:=0
9196      END;
9200      FLAG12:=0
9204      END;
9212
9212
9212
9212
9212 PROCEDURE TODISK;          (* STORE DATA ON DISK *)
9212 BEGIN
9212 REWRITE(FHST1);REWRITE(FHST2);
9220 IDUM:=USER(1);
9236 FOR I:=1 TO LASTM1 DO
9248 BEGIN
9256 F1:=FINHSTC1,I)*FBAR;
9284 WRITE(FHST1,F1);
9292 F2:=FINHSTC2,I)*FBAR;
9320 WRITE(FHST2,F2);
9328 END;
9348 RESET(FHST1);RESET(FHST2);
9356 IDUM:=USER(1);
9372 FLAG13:=0
9376 END;
9384
9384

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```

9384
9384
9384 PROCEDURE MANSET;          (* MANUAL FLOW CHECK AND SET *)
9384
9384 BEGIN
9384   IF MANUAL=0
9392     THEN WRITELN(" * ALL MODULES RECEIVING THE SAME FLOW")
9440     ELSE
9448       BEGIN
9448         WRITELN(" * MODULE NO.,MANUAL:2," IS SET AT A FLOW");
9504         WRITELN("  RATE OF",FLOWCMANUAL:4:0," LITRES/SEC");
9560         WRITELN;
9564         WRITELN(" * IS THE SETPOINT TO BE CHANGED? (Y/N)");
9612         READ(CHSET) ; WRITELN;
9624         IF CHSET="Y" THEN
9636           BEGIN
9636             WRITELN(" * ENTER THE NEW FLOW RATE SETTING FOR THIS MODULE"
9696             WRITELN("  IN UNITS OF LITRES/SEC (E.G. 100(RETURN))");
9752             READ(FLOWCMANUAL)
9768             END;
9768           END;
9768         WRITELN; WRITELN;
9776         POKE($7843,$95);
9796         IDUM:=USER(0);          (* ENABLE INTERRUPT *)
9812         POKE($7842,0);
9832         POKE($7809,0)          (* FLAG9=0 *)
9848       END;
9856
9856
9856
9856
9856 PROCEDURE TIMSET;          (* TIME CHECK AND SET *)
9856 VAR
9856   CHTIME   :CHAR;
9856
9856 BEGIN
9860   WRITELN;WRITELN;
9868   IF TIME>9
9876     THEN WRITELN(" * THE MACHINE TIME IS ",TIMEH:2,"H",TIMEM:2)
9932     ELSE WRITELN(" * THE MACHINE TIME IS ",TIMEH:2,"H0",TIMEM:1);
9996   WRITELN("  DO YOU WANT TO CHANGE TIME? Y/N");
10040  READ(CHTIME);
10048  WRITELN;
10052  IF CHTIME="Y" THEN
10064    BEGIN
10064      WRITELN(" * ENTER THE CORRECT TIME IN FORMAT HH MM(RETURN)");
10124      READ(TIMEH,TIMEM);
10140      WRITELN;
10144      MINOLD:=PEEK($7841);
10164      ITIME:=TIMEH*NINTPHR+1;
10180      ITIME:=ITIME+TIMEM DIV INTLEN;
10204      IDUM:=USER(5);          (* READ ADC'S *)
10220      PCVSTR:=22.0+PEEK($7813)*78.0/255;
10272      WRITELN;
10276      WRITELN(" *** NO MORE RESPONSES REQUIRED ***");
10320      WRITELN;
10324      INITL:=0;

```

```

10332     FLAG10:=1;
10340     FLAG11:=0
10344     END;
10348     WRITELN;
10352     POKE($7843,$95);
10372     IDUM:=USER(0);           (* ENABLE INTERRUPT *)
10388     POKE($7842,0);
10408     POKE($7808,0)           (* FLAG8=0 *)
10424     END;
10432
10432
10432
10432
10432 PROCEDURE CLOCK;              (* SOFTWARE CLOCK *)
10432 BEGIN
10432     IDUM:=USER(4);            (* LOOK AT CLOCK *)
10448     MINNEW:=PEEK($7841);
10468     IF MINNEW<>MINOLD THEN
10480     BEGIN
10480         IF MINOLD<MINNEW THEN TIMEM:=TIMEM+MINNEW-MINOLD;
10516         IF MINOLD>MINNEW THEN TIMEM:=TIMEM+4+MINNEW-MINOLD;
10556         IF TIMEM=60 THEN
10568         BEGIN
10568             TIMEM:=0;
10576             TIMEH:=TIMEH+1;
10588             IF TIMEH=24 THEN TIMEH:=0
10604             END;
10608             IF (TIMEH=7) AND (TIMEM=45) THEN FLAG3:=1;
10644             IF (TIMEH=12) AND (TIMEM=0) THEN FLAG13:=1;
10680             IF (TIMEH=19) AND (TIMEM=0) THEN
10708             BEGIN
10708                 IDUM:=USER(8);           (* LOOK AT DAY TYPE SWITCHES *)
10724                 JTODAY:=PEEK($7831);
10744                 JTOMOR:=PEEK($7832);
10764                 JNEXT:=PEEK($7833)
10772             END;
10784             IF (TIMEM MOD 10)=0 THEN FLAG14:=1
10804             END;
10808             MINOLD:=MINNEW
10808     END;
10820
10820
10820
10820
10820 PROCEDURE SERVCLOCK;          (* AT 5 MIN INTERVALS *)
10820
10820 PROCEDURE SETFLO;             (* SETS OUTFLOW RATES *)
10824
10824 FUNCTION CUBEROOT(VALUE:REAL):REAL;
10828     VAR
10828         ROOT    :REAL;
10828     BEGIN
10832         IF VALUE<1
10840             THEN CUBEROOT:=0
10848             ELSE
10860                 BEGIN

```



```

10860         ROOT:=1;
10872         REPEAT
10872             ROOT:=(VALUE/SQR(ROOT)+2*ROOT)/3
10908             UNTIL ABS(VALUE/(SQR(ROOT)*ROOT)-1)<1E-06;
10964             CUBEROOT:=ROOT;
10972         END;
10972     END;
10976
10976     BEGIN
10976         TOTFLOW:=FEXITCITIMEJ*FBAR-FLOWC[MANUAL];
11016         IF MANUAL=0 THEN TOTFLOW:=TOTFLOW/3
11036             ELSE TOTFLOW:=TOTFLOW/2;
11064         IF TOTFLOW>600 THEN TOTFLOW:=600;
11088         FOR I:=1 TO 3 DO
11100             IF MANUAL<>I THEN FLOWC[I]:=TOTFLOW;
11156         IF STARTUP=0 THEN
11168             BEGIN
11168                 FLAG12:=0;
11176                 FOR I:=1 TO 3 DO
11188                     BEGIN
11196                         NUMBER:=SQR(FLOWC[I]);
11216                         FLOWINTC[I]:=ROUND(3.2345*CUBEROOT(NUMBER))
11248                     END;
11276                 POKE($7821,FLOWINTC1);
11304                 POKE($7822,FLOWINTC2);
11332                 POKE($7823,FLOWINTC3);
11360                 POKE($7824,$07);
11380                 IDUM:=USER(6); (* WRITE TO DAC'S *)
11396                 STARTUP:=1;
11404             END;
11404         END;
11408
11408
11408     BEGIN (* CONTENTS OF SERVCLOCK *)
11408         IDUM:=USER(5); (* READ ADC'S *)
11424         PCVNOW:=22.0+PEEK($7813)*78.0/255;
11476         IF FLAGER=0 THEN FLAG12:=1;
11496         IF ((TIME MOD INTLEN)=0) AND (FLAGER=0) THEN
11532             BEGIN
11532                 ITIME:=ITIME+1;
11544                 IF ITIME=LAST THEN
11556                     BEGIN
11556                         ITIME:=1;
11564                         JYEST:=JTODAY;
11572                         JTODAY:=JTOMOR;
11580                         JTOMOR:=JNEXT
11580                     END;
11588                     PCVSTRT:=PCVNOW;
11596                     IDUM:=USER(1);
11612                     SETFLO;
11616                     FLAG10:=1;
11624                     FLAG11:=0
11628                 END;
11632                 FLAG14:=0
11636             END;
11644
11644

```

```

11644
11644
11644 BEGIN          (* CONTENTS OF CONTROL *)
11648   WRITELN;WRITELN;
11656   WRITELN("*****");
11700   WRITELN(" ", " 31,");
11728   WRITELN(" UNIVERSITY OF CAPE TOWN ");
11772   WRITELN(" EQUALIZATION CONTROL STRATEGY ");
11816   WRITELN(" ", " 31,");
11844   WRITELN("*****");
11888   WRITELN;
11892   WRITELN("WAIT FOR INPUT OF DATA FROM DISK");
11936   POKE($7843,$15);
11956   IDUM:=USER(0);          (* DISABLE INTERRUPT *)
11972   IDUM:=USER(3);          (* SET UP PIA *)
11988   WRITELN("PRESS CANCEL BUTTON");
12020   POKE ($7824,$00);
12040   IDUM:=USER(7);          (* SWITCH OFF LIGHTS *)
12056   LASTM1:=NINTPHR*24;
12068   LAST:=LASTM1+1;
12080   RESET(FHST1);
12084   FOR I:=1 TO LASTM1 DO READ(FHST1,FINHSTC1,I);
12144   RESET(FHST2);
12148   FOR I:=1 TO LASTM1 DO READ(FHST2,FINHSTC2,I);
12208   FSUM:=0;
12220   FOR I:=1 TO LASTM1 DO FSUM:=FSUM+FINHSTC1,I;
12288   FBAR:=FSUM/LASTM1;
12304   FOR J:=1 TO 2 DO
12316     FOR I:=1 TO LASTM1 DO FINHSTCJ,I:=FINHSTCJ,I/FBAR;
12424   FOR I:=1 TO LASTM1 DO
12436     BEGIN
12444       FEXITC1:=1.0;
12464       SIGNC1:=1;
12480       FINOLDC1:=0;
12500       FEXOLDC1,I:=0;
12524       FEXOLDC2,I:=0;
12548       FEXOLDC3,I:=0;
12572       PCVOLDC1:=0
12584     END;
12612   THT:=VOLUME/FBAR*1.0E06/(60.0*60.0);
12668   AMULT:=THT/100;
12684   DTC:=24.0/LASTM1;
12704   DTCAA:=DTC/AMULT;
12720   TIMEH:=0 ; TIMEV:=0;
12736   PRKT:=0;
12744   COPIES:=0;
12752   STARTUP:=0;
12760   MANUAL:=0 ; CHSET:="Z";
12776   FOR I:=0 TO 3 DO FLOWC1:=0.0;
12836   IDUM:=USER(8);          (* LOOK AT DAY TYPE SWITCHES *)
12852   JTODAY:=PEEK($7831);
12872   JTOMOR:=PEEK($7832);
12892   JNEXT:=PEEK($7833);
12912   INTLEN:=60 DIV NINTPHR;
12924   POKE($7800,0);          (* FLGOPT=0 *)
12944   POKE($7801,0);          (* FLAG1=0 *)
12964   POKE($7802,0);          (* FLAG2=0 *)

```

```

12984   POKE($7804,0);           (* FLAG4=0 *)
13004   POKE($7805,0);           (* FLAG5=0 *)
13024   POKE($7806,0);           (* FLAG6=0 *)
13044   POKE($7807,0);           (* FLAG7=0 *)
13064   POKE($7808,1);           (* FLAG8=1 *)
13084   POKE($7809,0);           (* FLAG9=0 *)
13104   FLAG3:=0;
13112   FLAG10:=0;
13120   FLAG11:=0;
13128   FLAG12:=0;
13136   FLAG13:=0;
13144   FLAG14:=0;
13152   FLAGER:=0;
13160   WRITELN;
13164   WRITELN("DATA INPUT COMPLETE---PROVIDE THE NECESSARY RESPONSES");
13228   WRITELN;WRITELN;
13236   WRITELN(" * ENTER THE LOWER TANK LEVEL LIMIT AS A % OF THE");
13296   WRITELN("  TOTAL TANK DEPTH. (E.G. 25(RETURN))");
13344   READ(BOTLIM) ; WRITELN;
13356   TOPM5:=TOPLIM-5;
13376   BOTP5:=BOTLIM+5;
13392   WRITELN(" * DO YOU WISH ANY OUTFLOWS TO BE MANUALLY SET? (Y/N)");
13456   READ(CHSET) ; WRITELN;
13468   IF CHSET="Y" THEN
13480     BEGIN
13480       WRITELN(" * WHICH MODULE'S FLOW IS TO BE SET MANUALLY?");
13536       WRITELN("  --- MODULE NO.1,NO.2,OR NO.3 ---");
13580       WRITELN("    ENTER ONE OF 1,2,OR 3(RETURN)");
13628       READ(MANUAL) ; WRITELN;
13640       WRITELN(" * ENTER THE FLOW RATE SETTING FOR THIS MODULE");
13696       WRITELN("  IN UNITS OF LITRES/SECOND (E.G. 100(RETURN))");
13752       READ(FLOWCMANUAL) ; WRITELN
13768     END;
13772   1:
13772   FLGOPT:=PEEK($7800) ; IF FLGOPT=1 THEN PRTOPT;
13808   FLAG1:=PEEK($7801) ; IF FLAG1=1 THEN PRINT1;
13844   FLAG2:=PEEK($7802) ; IF FLAG2=1 THEN PRINT2;
13880   FLAG4:=PEEK($7804) ; IF FLAG4=1 THEN PRINT4;
13916   FLAG5:=PEEK($7805) ; IF FLAG5=1 THEN PRINT5;
13952   FLAG6:=PEEK($7806) ; IF FLAG6=1 THEN PRINT6;
13988   FLAG7:=PEEK($7807) ; IF FLAG7=1 THEN PRINT7;
14024   FLAG8:=PEEK($7808) ; IF FLAG8=1 THEN TIMSET;
14060   FLAG9:=PEEK($7809) ; IF FLAG9=1 THEN MANSET;
14096   IDUM:=USER(1);           (* PROGRAM ACTIVE PULSE *)
14112   IF FLAG3=1 THEN PRINT3;
14128   IF FLAG10=1 THEN INITIAL;
14144   IF FLAG11=1 THEN OPTIMUM;
14160   IF FLAG13=1 THEN TODISK;
14176   CLOCK;
14180   IF FLAG14=1 THEN SERVCLOCK;
14196   IF FLAG12=1 THEN EMERGE;
14212   GOTO 1;
14216   END.
14220   BYTES
      END OF PASS 1
      END OF PASS 2
      OK TO RUN

```

E.1.2 Listing of program MACHCD

```

+++ASMB MACHCD
DELETE OLD BINARY (Y-N)? Y
* KEYBOARD INTERRUPT PROCESSING
NAM MACHCD
E004 ACIAS EQU $E004
E005 ACIAD EQU $E005
000D CR EQU $0D
000A LF EQU $0A
DFCB INTVEC EQU $DFCB
0140 DEVINT EQU $0140
014B LIMIT EQU $014B
0144 USRENT EQU $0144
0146 MARKUS EQU $0146
F80A OUTCH EQU $F80A
F810 PSTRNG EQU $F810
E030 ADC0 EQU $E030
E031 ADC1 EQU $E031
E032 ADC2 EQU $E032
E033 ADC3 EQU $E033
E070 PIAA EQU $E070
E072 PIAB EQU $E072
E07F LATCH EQU $E07F
7800 FLG0FT EQU $7800
7801 FLAG1 EQU $7801
7802 FLAG2 EQU $7802
7803 FLAG3 EQU $7803
7804 FLAG4 EQU $7804
7805 FLAG5 EQU $7805
7806 FLAG6 EQU $7806
7807 FLAG7 EQU $7807
7808 FLAG8 EQU $7808
7809 FLAG9 EQU $7809
7810 FLOW1 EQU $7810
7811 FLOW2 EQU $7811
7812 FLOW3 EQU $7812
7813 VOL EQU $7813

INTRPT VECTOR LOCATION
DEVICE INITIALISATION
MACH CD ENTRY POINT
INDIRECT OUTCH VECT.

```

7821	FSET1	EQU	\$7821	DEVINT	ADDR OF INITILISATION
7822	FSET2	EQU	\$7822	INITL	
7823	FSET3	EQU	\$7823	LIMIT	
7824	VALVE	EQU	\$7824	\$7400	MAX EXTENT OF PASCAL
7825	DUMLAT	EQU	\$7825	INTVEC	
7831	DAY1	EQU	\$7831	INTER	ADDR OF INTRPT ROUTINE
7832	DAY2	EQU	\$7832	USRENT	
7833	DAY3	EQU	\$7833	START	USER ENTRY POINT
	*				
0140		ORG			
0140	743C	FDB			
0148		ORG			
0148	7400	FDB			
DFC8		ORG			
DFC8	744D	FDB			
0144		ORG			
0144	7400	FDB			
	*				
7840		ORG	\$7840		STORAGE SPACE FOR
7840		RMB		VARIABLES ETC	
7841	00	FCB	1		
7842	00	FCB	0		
7843	95	FCB	%10010101		
7844	7846	FDB	BUFFER		
7846		RMB	10		
	*				

			*		
7400		ORG	\$7400		JUMP TABLE
7400	BE	EQU	*		
7403	A6	LDX	MARKUS		
7405	B1	LDA	9,X		
7407	1027 0031	CMPLA	#00		
7408	B1	LBEQ	INITL		
740D	1027 0198	CMPLA	#01		
		LBEQ	MCPULS		


```

7460 BE 7844          GET BUFFER POINTER
7463 A7 80          STORE & INCR. X
7465 BF 7844        RESTORE POINTER
7468 3B            RETURN

*
7469 AD 9F F80A      CRPRDC          PRINT THE CR
746D B6 0A          LDA #LF          LINEFEED
746F AD 9F F80A      JSR COUTCHJ     PRINT IT
7473 BE 7846        LDX #BUFFER
7476 BF 7844        STX BUFPTR       RESET POINTER

*
*
* READY FOR TESTING INPUT & PROCESSING IT
*
* TEST IF CONVERSATION ACTIVE
7479 7D 7842        TST TALKNG      KEYBD INTERACTION ACTIVE?
747C 1026 0096      LBNE OPTNS      GOTO OPTION PROC.

*
* TEST IF INPUT = *HELLO*
7480 8E 7846        LDX #BUFFER     START ADDR OF BUFFER
7483 A6 80          LDA ,X+
7485 B1 48          CMPA #'H         ?H
7487 26 31          BNE FAIL
7489 A6 80          LDA ,X+
748B B1 45          CMPA #'E         ?E
748D 26 2B          BNE FAIL
748F A6 80          LDA ,X+
7491 B1 4C          CMPA #'L         ?L
7493 26 25          BNE FAIL
7495 A6 80          LDA ,X+
7497 B1 4C          CMPA #'L         ?L
7499 26 1F          BNE FAIL
749B A6 80          LDA ,X+
749D B1 4F          CMPA #'O         ?O
749F 26 19          BNE FAIL
74A1 86 01          LDA #1
74A3 B7 7842        STA TALKNG      SET "ACTIVE" INDICATOR

```

74A6 8E	74BC					
74A9 AD	9F F810	*				
74AD BE	7844					
74E0 C6	06					
74E2 86	20					
74E4 A7	80					
74E6 5A			BLANK			
74E7 26	FB					
74E9 3B						
74EA 12			FAIL			
74EB 3B		*				
74EC 48	45 4C 4C		MSG1			
74C0 4F	21 20 2D					
74C4 20	43 6F 72					
74C8 72	65 63 74					
74CC 20	65 6E 74					
74D0 72	79 21					
74D3 0D	0A					
74D5 20	53 50 45					
74D9 43	49 46 59					
74DD 20	4F 50 54					
74E1 49	4F 4E 20					
74E5 4E	55 4D 42					
74E9 45	52 20 28					
74ED 43	2E 52 2E					
74F1 29	0D 0A					
74F4 20	49 46 20					
74F8 55	4E 53 55					
74FC 52	45 20 4F					
7500 46	20 4F 50					
7504 54	2E 20 4E					
7508 4F	2E 20 45					
750C 4E	54 45 52					
7510 20	50 0D 0A					
7514 0A	04					

LDX	MSG1		
JSR	LPSTRNGJ		
LDX	BUFPTR		
LDB	#6		BLANK OUT BUFFER
LDA	#\$20		
STA	0,X+		
DECB			
BNE	BLANK		
RTI			
NOP			NO MATCH
RTI			
FCC	*HELLO! - Correct entry!*		
FCC	CR,LF		
FCC	* SPECIFY OPTION NUMBER (C.R.)*,CR,LF		
FCC	* IF UNSURE OF OPT. NO. ENTER P*,CR,LF,LF,4		

* OPTNS		OPTION PROCESSING	
7516 12	7846	NOF	BUFFER
7517 B6	50	LDA	#'P
751A 81	57	CMFA	OPTP
751C 27	31	BEG	#'1
751E 81	58	CMFA	OPT1
7520 27	32	BEG	#'2
7522 81	59	CMFA	OPT2
7524 27	34	BEG	#'4
7526 81	5A	CMFA	OPT4
7528 27	35	BEG	#'5
752A 81	5B	CMFA	OPT5
752C 27	36	BEG	#'6
752E 81	005A	CMFA	OPT6
>7530 1027	37	LBEQ	#'7
7534 81	0059	CMFA	OPT7
>7536 1027	38	LBEQ	#'8
753A 81	0058	CMFA	OPT8
>753C 1027	39	LBEQ	#'9
7540 81	0057	CMFA	OPT9
>7542 1027	7551	LBEQ	MSG2
7546 8E	9F'F810	LDX	CPSTRNGI
7549 AD	7842	JSR	TALKNG
754D 7F		CLR	
7550 3B		RTI	
* MSG2		* AND SUCH OPTION *	
7551 4E 4F 20 53		FCC	
7555 55 43 48 20			
7559 4F 50 54 49			
755D 4F 4E 20 20			
7561 20 20 20 20			
7565 20			
7566 1B 70		FCB	\$1B,'p
7568 47 4F 4F 44		FCC	*GOODBYE*
756C 42 59 45			
756F 0D 0A 0A 1B		FCB	CR,LF,LF,\$1B,'q,4
7573 71 04			

```

7575 7C      * OPTP      INC      FLGOPT      OPEN PRTOPT PROCEDURE
7578 20      * OPT1      INC      DISABL      OPEN PRTOPT PROCEDURE
757A 7C      * OPT1      INC      FLAG1       OPEN PRTOPT PROCEDURE
757D 20      * OPT2      INC      DISABL      OPEN PRTOPT PROCEDURE
757F 7C      * OPT2      INC      FLAG2       OPEN PRTOPT PROCEDURE
7582 20      * OPT4      INC      DISABL      OPEN PRTOPT PROCEDURE
7584 7C      * OPT4      INC      FLAG4       OPEN PRTOPT PROCEDURE
7587 20      * OPT5      INC      DISABL      OPEN PRTOPT PROCEDURE
7589 7C      * OPT5      INC      FLAG5       OPEN PRTOPT PROCEDURE
758C 20      * OPT6      INC      DISABL      OPEN PRTOPT PROCEDURE
758E 7C      * OPT6      INC      FLAG6       OPEN PRTOPT PROCEDURE
7591 20      * OPT7      INC      DISABL      OPEN PRTOPT PROCEDURE
7593 7C      * OPT7      INC      FLAG7       OPEN PRTOPT PROCEDURE
7596 20      * OPT8      INC      DISABL      OPEN PRTOPT PROCEDURE
7598 7C      * OPT8      INC      FLAG8       OPEN PRTOPT PROCEDURE
759B 20      * OPT9      INC      DISABL      OPEN PRTOPT PROCEDURE
759D 7C      * OPT9      INC      FLAG9       OPEN PRTOPT PROCEDURE
75A0 86      * DISABL    LDA      #15         OFFSET INTRPT
75A2 B7      * DISABL    STAA     ACCODE      OFFSET INTRPT
75A5 BD      * DISABL    JSR      INITL       OFFSET INTRPT
75A8 3B      * DISABL    RTI                OFFSET INTRPT

*****
* MCFULS      LDX      #DUMLAT      FULSER
* MCFULS      LDB      #FE         FULSER
* MCFULS      ANDB     0,X         FULSER
* MCFULS      STB      0,X         FULSER
* MCFULS      LDA      DUMLAT      FULSER
* MCFULS      STA      LATCH      FULSER
* MCFULS      LDB      #01         FULSER
* MCFULS      ORB      0,X         FULSER
* MCFULS      STB      0,X         FULSER
* MCFULS      LDA      DUMLAT      FULSER
* MCFULS      STA      LATCH      FULSER
* MCFULS      RTS

```

```

*
* *****
*
75C5 8E 7825 MCALRM LDX #DUMLAT ALARM
75C8 C6 FD LDB #FED
75CA E4 84 ANDB 0,X
75CC E7 84 STB 0,X
75CE B6 7825 LDA DUMLAT
75D1 B7 E07F STA LATCH
75D4 C6 02 LDB #02
75D6 EA 84 ORB 0,X
75D8 E7 84 STB 0,X
75DA B6 7825 LDA DUMLAT
75DD B7 E07F STA LATCH
75E0 39 RTS

*
* *****
*
75E1 86 03 MCPA LDA #03 SET UP PIA
75E3 B7 E07F STA LATCH
75E6 B7 7825 STA DUMLAT
* B0=1...SIDE A OUTPUTS
* B1=0...SIDE B INPUTS
*
* SET UP A SIDE ... OUTPUTS
75E9 8E E070 LDX #PIAA
75EC 6F 01 CLR 1,X
75EE 86 FF LDA #FFF
75F0 A7 84 STA 0,X
75F2 86 04 LDA #04
75F4 A7 01 STA 1,X
SELECT D.D.R.
1'S FOR OUTPUTS
INSERT 1'S IN D.D.R.
SELECT DATA REGISTER...B2=1
INSERT IN CONTROL REGISTER

*
* SET UP B SIDE ... INPUTS
75F6 8E E072 LDX #PIAB
75F9 6F 01 CLR 1,X
75FB 86 00 LDA #00
75FD A7 84 STA 0,X
SELECT D.D.R.
0'S FOR INPUTS
INSERT 0'S IN D.D.R.

```

```

75FF 86 04          LDA      #004          SELECT DATA REGISTER...B2=1
7601 A7 01          STA      1,X          INSERT IN CONTROL REGISTER
7603 39             RTS

*
*****
*
MCCLOK  LDX      #PIAB          PIA SIDE B   BINARY CLOCK
        JSR      TST0          TEST XIT 0
        BNE      LB2           BIT 0 SET.. MUST BE 1 OR 3
E072    LDX      #PIAB          BIT 0 CLEAR..MUST BE 0 OR 2
7633    JSR      TST1          BIT 1 SET..MUST BE A 2
13      BNE      LB1           BIT 1 CLEAR..MUST BE A 0
E072    CLRA      CLOCK        SET CLOCK TO 0
7637    ST.      RTS
05      LDA      #02          SET CLOCK TO 2
7641    STAA     RTS
02      LDX      #PIAB          BIT 2 SET..MUST BE A 3
7641    JSR      TST1          BIT 2 CLEAR..MUST BE A 1
E072    BNE      LB3           SET CLOCK TO 1
7637    LDA      #01          SET CLOCK TO 3
06      STAA     RTS
01      LDA      #03          SET CLOCK TO 3
7641    STAA     RTS
03      LDX      #01          TST0
7632    JSR      OUTT          #01
04      LDX      #02          TST1
7637    JSR      OUTT          #02
02      BNE      OUTT          OUTT 0,X
00      RTS
84      RTS
763D 39             RTS

*
*****
*

```

ADC READ PROGRAM

```

763E 86 00          LDA #00
7640 E7 E030        STAA ADC0
>7643 BD 7677        JSR DLAY
7646 E6 E030        LDA ADC0
7649 E7 7810        STA FLOW1

```

*

```

764C 86 00          LDA #00
764E E7 E031        STAA ADC1
>7651 BD 7677        JSR DLAY
7654 E6 E031        LDA ADC1
7657 E7 7811        STA FLOW2

```

*

```

765A 86 00          LDA #00
765C E7 E032        STAA ADC2
>765F BD 7677        JSR DLAY
7662 E6 E032        LDA ADC2
7665 E7 7812        STA FLOW3

```

*

```

7668 86 00          LDA #00
766A E7 E033        STAA ADC3
>766D BD 7677        JSR DLAY
7670 E6 E033        LDA ADC3
7673 E7 7813        STA VOL
7676 39             RTS

```

*

```

7677 8E 00FF        LDX #00FF
767A 30 1F          DEX
767C 26 FC          BNE LOOP
767E 39             RTS

```

*

*

DAC WRITE PROGRAM

```

767F 8E 7825        LDX #DUMLAT
7682 E6 7821        LDA FSET1
7685 E7 E070        STA FIAA
7688 BD 18          BSR STROB1
768A E6 7822        LDA FSET2

```

768D B7	E070		STA	PIAA
7690 8D	18		BSR	STROB2
7692 B6	7823		LDA	FSET3
7695 B7	E070		STA	PIAA
7698 8D	18		BSR	STROB3
769A B6	7824	SETUP	LDA	VALVE
769D B7	E070		STA	PIAA
76A0 20	18		BRA	STROB4
76A2 C6	10	* STROB1	LDB	#10
76A4 8D	1C		BSR	OUTS
76A6 C6	EF		LDB	#EF
76A8 20	23		BRA	OUTC
76AA C6	20	* STROB2	LDB	#20
76AC 8D	14		BSR	OUTS
76AE C6	DF		LDB	#DF
76B0 20	1B		BRA	OUTC
76B2 C6	40	* STROB3	LDB	#40
76B4 8D	0C		BSR	OUTS
76B6 C6	BF		LDB	#BF
76B8 20	13		BRA	OUTC
76BA C6	80	* STROB4	LDB	#80
76BC 8D	04		BSR	OUTS
76BE C6	7F		LDB	#7F
76C0 20	0B		BRA	OUTC
76C2 EA	84	* OUTS	ORB	0,X
76C4 E7	84		STB	0,X
76C6 B6	7825		LDA	DUMLAT
76C9 B7	E07F		STA	LATCH
76CC 39		* OUTC	RTS	
76CD E4	84		ANDB	0,X
76CF E7	84		STB	0,X

```

76D1 B6 7825          LDA      DUMLAT
76D4 B7 E07F          STA      LATCH
76D7 39              RTS

76D8 8E 7825          * MCLITE  LDX      #DUMLAT  LIGHTS OFF
>76DB 7E 769A          JMP      SETUP

* *****
* *****
* *****
MCDAY                TEST DAY TYPE SWITCHES
76DE 8E E072          LDX      #FIAB
>76E1 BD 7714          JSR      TST2
76E4 27 07            BEQ      X1
76E6 86 02            LDA      #02
76E8 B7 7831          STA      DAY1
76EB 20 05            BRA      X2
76ED 86 01            LDA      #01
76EF B7 7831          STA      DAY1

* X1
* X2
>76F2 BD 7718          JSR      TST3
76F5 27 07            BEQ      X3
76F7 86 02            LDA      #02
76F9 B7 7832          STA      DAY2
76FC 20 05            BRA      X4
76FE 86 01            LDA      #01
7700 B7 7832          STA      DAY2

* X3
* X4
>7703 BD 771C          JSR      TST4
7706 27 06            BEQ      X5
7708 86 02            LDA      #02
770A B7 7833          STA      DAY3
770D 39              RTS
770E 86 01            LDA      #01
7710 B7 7833          STA      DAY3
7713 39              RTS

* X5
* TST2
7714 C6 04            LDAB     #04
7716 20 06            BRA      OUTB

```

```

7718 C6 08 LDAB #00B
771A 20 02 BRA OUTB
771C C6 10 LDAB #10
771E E5 84 BITB 0,X
7720 39 RTS

```

```

*
```

```

*
```

```

*****

```

```

END

```

```

0 ERROR(S) DETECTED

```

```

SYMBOL TABLE:

```

ACCODE 7843	ACIAD	E005	ACIAS	E004	ADC0	E030	ADC1	E031
ADC2 E032	ADC3	E033	BLANK	74B4	BUFFER	7846	BUFFTR	7844
CLOCK 7841	CR	0000	CRPROC	7469	DAY1	7831	DAY2	7832
DAY3 7833	DEVINT	0140	DISABL	75A0	DLAY	7677	DUMLAT	7825
FAIL 74BA	FLAG1	7801	FLAG2	7802	FLAG3	7803	FLAG4	7804
FLAGS 7805	FLAG6	7806	FLAG7	7807	FLAG8	7808	FLAG9	7809
FLGOPT 7800	FLOW1	7810	FLOW2	7811	FLOW3	7812	FSET1	7821
FSET2 7822	FSET3	7823	INITL	743C	INTER	744D	INTVEC	DFC8
LATCH E07F	LB1	7619	LB2	761F	LB3	762D	LF	000A
LIMIT 0148	LOOP	767A	MARKUS	0146	MCADC	763E	MCALRM	75C5
MCCLOK 7604	MCDAC	767F	MCDAY	76DE	MCLITE	76D8	MCPIA	75E1
MCPULS 75A9	MSG1	74BC	MSG2	7551	OPT1	757A	OPT2	757F
OPT4 7584	OPT5	7589	OPT6	758E	OPT7	7593	OPT8	7598
OPT9 759D	OPTNS	7516	OPTP	7575	OUTB	771E	OUTC	76CD
OUTCH F80A	OUTS	76C2	OUTT	763B	PIAA	E070	PIAB	E072
PSTRNG F810	RDCHAR	7455	SETUP	769A	START	7400	STROB1	76A2
STROB2 76AA	STROB3	76B2	STROB4	76BA	TALKNG	7842	TST0	7633
TST1 7637	TST2	7714	TST3	771B	TST4	771C	USRENT	0144
VALVE 7824	VOL	7813	X1	76ED	X2	76F2	X3	76FE
X4 7703	X5	770E						

E.2 Documentation of Operating Procedures

Before handing over control of the microcomputer to the operating staff of the Goudkoppies plant it was necessary to prepare detailed step-by-step instructions for the operation of the equipment. Three sets of instructions covering different aspects of the operation were prepared for the Plant Manager. These instructions are distributed amongst the plant operators at the discretion of the Manager, depending on the level of competence of individual operators. The three sets of instructions are

- START-UP PROCEDURE FOR COMPUTER CONTROL OF GOUDKOPPIE
BALANCING TANK*
- DAILY MAINTENANCE PROCEDURE FOR COMPUTER CONTROL OF GOUDKOPPIE
BALANCING TANK
- DATA RETRIEVAL PROCEDURE FOR COMPUTER CONTROL OF GOUDKOPPIE
BALANCING TANK

The three sets of instructions are listed in the pages which follow. A comment which has been made regarding these instructions is that they may be over-simplistic. However, it should be remembered that these have been prepared for use by personnel with little or no previous experience with computer terminal usage; therefore it is necessary to document the procedures in explicit, step-by-step detail.

* One slight change has been made to the software: between Steps 8 and 9 in the "Start-up Procedure" the computer prompts for the lower allowable hold-up limit as a percentage of the total (see Section E.3).

START-UP PROCEDURE FOR COMPUTER CONTROL OF GOUDKOPPIE BALANCING TANK

The following step-by-step procedure should be followed in order to activate computer control of the balancing tank outlets. The procedure would typically be used on :-

- (a) Initial start-up of the system
- (b) Re-initialisation of the system after a power failure.
- (c) Re-initialisation of the system after servicing of the flow controllers.

This procedure is only required in one of the above instances; it should be seen as being separate from the "Daily Maintenance" or "Information Retrieval" procedures.

STEP 1

Open the gate of the Floppy Disk Drive. Carefully remove the disk from the Drive and place it in a disk envelope (leave the gate open).

STEP 2

Switch off the wall plug supplying 220 V to the plug-board with four sockets.

STEP 3

Carry out the following procedure on the panel of the wooden Interface box :-

- (a) Ensure that the Trip/Override Switch is in the position "Override".
- (b) Ensure that the three switches below the three meters are in the "Up for Local Setpoint" position.
- (c) Ensure that the three Day Type Switches ("Today", "Tomorrow" and "Next") are in the correct positions - up for a weekday and down for a weekend or public holiday.

- 2 -

STEP 4

Switch on the wall plug. The terminal will make a 'beep' sound. After about 1½ minutes, when the terminal screen has warmed up, the following message will be seen on the screen

```
S - BUG    1.5    -    40 K
>
```

STEP 5

Carefully slide the floppy disk into the Disk Drive. The floppy disk is inserted with :-

- (a) the "Verbatim" label on the left at the top.
- (b) The pink arrow on the label pointing into the slot, and
- (c) the square notch in the edge of the disk at the bottom.

Close the gate of the Disk Drive.

STEP 6

Carry out the following procedure on the keyboard of the terminal :

- (a) Type in a U and wait. After about 30 seconds, the following will appear on the screen :-

```
S - BUG    1.5    -    40 K
>  U
FLEX    9.0
DATE    (MM, DD, YY) ?
```

- (b) Type in "1" space "1" space "1" , tap the key marked "RETURN" and wait. After a few seconds the screen will show the following :-

```
S - BUG    1.5    -    40 K
>  U
FLEX    9.0
DATE    (MM, DD, YY) ?    1    1    1
+  +  +
```

- 3 -

STEP 7

Press the red "Start" button on the interface panel. The light below the "Power" label and the three lights above each of the meters will be on, and the three meters will show readings of about 70 .

STEP 8

Type in the following on the keyboard :

"EXEC" space "GOUD" , tap the key marked "RETURN" and wait

Over a period of about 2 minutes the following will appear on the screen :

+ + + EXEC GOUD

P-6800 RUN-TIME SYSTEM V 2.9 : COPYRIGHT C 1980 LUCIDATA

* * * * *

* * *

* UNIVERSITY OF CAPE TOWN *

* EQUALISATION CONTROL STRATEGY *

* * *

* * * * *

WAIT FOR INPUT OF DATA FROM DISK

PRESS CANEL BUTTON

DATA INPUT COMPLETE - - - - - PROVIDE THE NECESSARY RESPONSES

* DO YOU WISH ANY OUTFLOWS TO BE MANUALLY SET ? (Y/N)

STEP 9

At this stage the three lights above each of the meters will be off. The responses required by the computer are all self-explanatory.

However, for purposes of clarity, the procedure is demonstrated below :-

- 4 -

(a) To the question

* DO YOU WISH ANY OUTFLOWS TO BE MANUALLY SET ? (Y/N)

either type in a "Y" if the answer is 'Yes' or an "N" if the answer is 'No'

Typically a set flow in Module 3 will be required, so a "Y" will be typed.

(b) If a "Y" is entered, then the following will appear on the screen :-

* WHICH MODULE'S FLOW IS TO BE SET MANUALLY ?

- - - MODULE NO 1 , NO 2 , OR NO 3 - - -

ENTER ONE OF 1 , 2 OR 3 (RETURN)

If say, Module 3 is to be set at a particular flow, then type in "3" and tap the "RETURN" key .

(c) The following will then appear on the screen :-

* ENTER THE FLOW RATE SETTING FOR THIS MODULE IN UNITS OF LITRES/SECOND (E.G 100 (RETURN))

If a flow rate of say 300 l/s is required for the specified Module then type in "300" and tap the "RETURN" key.

(d) The following will then appear on the screen :-

* THE MACHINE TIME IS OHOO

DO YOU WANT TO CHANGE TIME ? (Y/N)

Type in a Y

The screen will then show

* ENTER THE CORRECT TIME IN FORMAT HH MM (RETURN)

- 5 -

If the time is say, 9.25 am then type in "0 9" space "25"
and tap the "RETURN" key.

If the time is say, 2.05 pm then type in "14" space "05"
and tap the "RETURN" key.

The computer then responds with

*** NO MORE RESPONSES REQUIRED ***

indicating that no further action on the keyboard is required.

STEP 10

Change the position of the three switches below each of the meters to the position

"Down for Automatic Control" . On the next half-hour the three lights above the meters will come on.

STEP 11

Change the position of the Trip/Override Switch on the Interface panel to "Trip" .

DAILY MAINTENANCE PROCEDURE FOR COMPUTER CONTROL OF GOUDKOPPIE BALANCING TANK

The following procedure should be followed each day between 10 after the hour and 10 to the hour.

STEP 1

Carry out the following actions on the Interface panel :-

- (a) Switch the Override/Trip Switch to the "Override" position.
- (b) Check that the three Day Type Switches (Today, Tomorrow and Next) are in the correct positions.
- (c) Check that the three lights above the three meters are on. If these are not, bring to the attention of the Plant Manager.
- (d) Check that the three switches below the three meters are in the "Down for Automatic Control" position.

STEP 2

On the terminal keyboard type in "HELLO" and tap the "RETURN" key.

After a few seconds, the following will appear on the screen :-

```
HELLO
HELLO ! - Correct entry !
SPECIFY OPTION NUMBER (C.R)
IF UNSURE OF OPT. NO. ENTER P
```

STEP 3

Type in an "8" and tap the "RETURN" key.

After a few seconds the

following will appear on the screen :-

```
8
* THE MACHINE TIME IS 12H15
DO YOU WANT TO CHANGE TIME ? Y/N
```

- 2 -

STEP 4

- (a) If the machine time is correct then type in an "N" .
- (b) If the machine time is incorrect then type in a "Y".

The following will then appear on the screen :-

* ENTER THE CORRECT TIME IN FORMAT HH MM (RETURN)

If the time is say, 9.25 am then type in

"09" space "25" and tap the "RETURN" key

If the time is say, 3.40 pm then type in

"15" space "40" and tap the "RETURN" key

The following message then appears on the screen :-

*** NO MORE RESPONSES REQUIRED ***

STEP 5

Switch the Override/Trip Switch on the Interface panel to the "Trip" position.

IF FURTHER INFORMATION REGARDING THE COMPUTER OPERATION IS
REQUIRED THEN CONSULT THE "DATA RETRIEVAL" PROCEDURE

12 March 1981

/jb

DATA RETRIEVAL PROCEDURE FOR COMPUTER CONTROL OF GOUDKOPPIE BALANCING TANK

The computer linked to the Goudkoppie Balancing Tank can supply certain information concerning the operation of the process. Before attempting to obtain any of this information, it is of utmost importance to

ENSURE THAT ALL RESPONSES REQUESTED BY THE COMPUTER ARE ANSWERED

STEP 1

On the Interface panel switch the Override/Trip Switch to the "Override" position

STEP 2

On the terminal keyboard type in "HELLO" and tap the "RETURN" key.
The following will then appear on the screen :-

```
HELLO
HELLO ! - Correct entry !
SPECIFY OPTION NUMBER   (C.R.)
IF UNSURE OF OPT. NO. ENTER    P
```

STEP 3

Type in the required option number, and tap the "RETURN" key.

After a few seconds information will appear on the screen and on the Printer.

The possible interrupt options are as follows :-

<u>OPT. NO.</u>	<u>ACTION</u>
1	PRINT INPUT DATA
2	PRINT HISTORICAL INFLOW DATA
4	PRINT EXPECTED RESULTS FOR NEXT 24 HOURS
5	PRINT LEVEL SENSOR READING
6	PRINT CURRENT ERROR EXPRESSION VALUES

(continued overleaf)

- 2 -

- 7 COMPARE ACTUAL AND REQUESTED OUTFLOWS
- 8 CHECK AND/OR CHANGE TIKE OF DAY
- 9 CHECK AND/OR CHANGE FLOW TO MOD. 3

Normally the only options requested would 2, 4, 5, 7, 8 and 9 .

STEP 4

ENSURE THAT ANY REQUIRED RESPONSES HAVE BEEN SUPPLIED !

STEP 5

If all required information has been supplied then set the Override/Trip Switch on the Interface panel to the "TRIP" position.

12 March 1981

/jb

Steps 1 to 5 of the Start-up Procedure involve initializing the disc drive, interface and power supply. The remaining steps are concerned with "booting" the microprocessor, and then responding to the various requests for input; the printout below gives an example of this phase of the start-up procedure.

S-BUG 1.5 - 40K

>U
FLEX 9.0

DATE (MM,DD,YY)? 1 1 1

***EXEC GOUL

R-6800 RUN-TIME SYSTEM V 2.7 : COPYRIGHT C 1980 LUCIDATA

```
*****
*
*   UNIVERSITY OF CAPE TOWN   *
* EQUALIZATION CONTROL STRATEGY *
*
*****
```

WAIT FOR INPUT OF DATA FROM DISK
PRESS CANCEL BUTTON

DATA INPUT COMPLETE---PROVIDE THE NECESSARY RESPONSES

* ENTER THE LOWER TANK LEVEL LIMIT AS A % OF THE
TOTAL TANK DEPTH. (E.G. 25(RETURN))

10

* DO YOU WISH ANY OUTFLOWS TO BE MANUALLY SET? (Y/N)

Y

* WHICH MODULE'S FLOW IS TO BE SET MANUALLY?

--- MODULE NO.1,NO.2,OR NO.3 ---

ENTER ONE OF 1,2,OR 3(RETURN)

3

* ENTER THE FLOW RATE SETTING FOR THIS MODULE
IN UNITS OF LITRES/SECOND (E.G. 100(RETURN))

200

* THE MACHINE TIME IS 0H00
DO YOU WANT TO CHANGE TIME? Y/N

Y

* ENTER THE CORRECT TIME IN FORMAT HH MM(RETURN)

12 25

*** NO MORE RESPONSES REQUIRED ***

E.3 Examples of Printed Output

During normal operation of the microcomputer execution can be interrupted from the keyboard to allow requests for output (see Section 4.1.2, Chapter 7). The password HELLO must be typed in on the keyboard before a request for output can be made. On typing HELLO the microcomputer responds with the message

```
HELLO
```

```
HELLO! - Correct entry!
SPECIFY OPTION NUMBER (C.R.)
IF UNSURE OF OPT. NO. ENTER P
```

The various options for printed output are detailed in the "Data Retrieval Instructions" documented in Section E.3; an example of the output supplied with each option is now presented.

Option P*:

LIST OF INTERRUPT OPTIONS

OPT. NO.	ACTION
1	PRINT INPUT DATA
2	PRINT HISTORICAL INFLOW DATA
4	PRINT EXPECTED RESULTS FOR NEXT 24 HOURS
5	PRINT LEVEL SENSOR READING
6	PRINT CURRENT ERROR EXPRESSION VALUES
7	COMPARE ACTUAL AND REQUESTED OUTFLOWS
8	CHECK AND/OR CHANGE TIME OF DAY

Option 1:

```
*****
PROCESS INFORMATION
*****
```

```
MEAN TANK RETENTION TIME (HOURS) = 4.75
```

```
TANK HOLD-UP LIMITS (%):
    MAXIMUM = 95.0
    MINIMUM = 10.0
```

```
ERROR EXPRESSION WEIGHTING FACTORS :
    BETA  =1.9999E-06
    ZETA  =25.0
```

```
MINIMUM FLOW INCREMENT = 0.02
```

* An additional option (No.9) is listed if the outflow rate from one of the tank outlets has been specified during the start-up procedure.

Option 2:

 HISTORICAL DATA

TIME	INFLOW RATE DATA (AVERAGE, L/S)	
	WEEKDAY	WEEKEND
0H00	996	557
0H30	920	555
1H00	896	551
1H30	865	533
2H00	844	523
2H30	821	510
3H00	800	489
3H30	762	479
4H00	706	469
4H30	720	475
5H00	752	477
5H30	777	485
6H00	801	500
6H30	825	525
7H00	851	553
7H30	980	578
8H00	1063	587
8H30	1200	700
9H00	1366	785
9H30	1500	1000
10H00	1800	1044
10H30	1710	1100
11H00	1821	1108
11H30	1840	1135
12H00	1850	1147
12H30	1880	1150
13H00	1900	1150
13H30	1892	1100
14H00	1884	1080
14H30	1856	1075
15H00	1835	1068
15H30	1805	1060
16H00	1783	1054
16H30	1725	1000
17H00	1695	923
17H30	1645	890
18H00	1597	820
18H30	1555	850
19H00	1500	855
19H30	1450	840
20H00	1400	829
20H30	1400	820
21H00	1396	806
21H30	1350	790
22H00	1298	760
22H30	1240	740
23H00	1200	680
23H30	1100	620

Option 4:

 OPTIMUM RESULTS FOR NEXT 24 HOURS

TIME	EXPECTED INFLOW L/S	OPTIMUM OUTFLOW L/S	EXPECTED HOLDUP (%)
17H30	1645	1330	79.3
18H00	1597	1330	81.8
18H30	1555	1330	83.9
19H00	1500	1330	85.7
19H30	1450	1330	87.1
20H00	1400	1330	88.0
20H30	1400	1330	88.6
21H00	1396	1330	89.1
21H30	1350	1330	89.6
22H00	1298	1330	89.8
22H30	1240	1330	89.5
23H00	1200	1330	88.8
23H30	1100	1330	87.8
0H00	996	1330	86.0
0H30	920	1330	83.3
1H00	896	1330	80.1
1H30	865	1330	76.6
2H00	844	1330	73.0
2H30	821	1330	69.1
3H00	800	1330	65.1
3H30	762	1330	60.9
4H00	706	1330	56.4
4H30	720	1330	51.4
5H00	752	1330	46.6
5H30	777	1330	42.0
6H00	801	1330	37.7
6H30	825	1330	33.5
7H00	851	1330	29.5
7H30	980	1330	25.7
8H00	1063	1330	22.9
8H30	1200	1330	20.8
9H00	1366	1330	19.8
9H30	1500	1330	20.1
10H00	1800	1330	21.4
10H30	1710	1330	25.1
11H00	1821	1330	28.1
11H30	1840	1330	32.0
12H00	1850	1330	36.0
12H30	1880	1330	40.1
13H00	1900	1330	44.5
13H30	1892	1330	49.0
14H00	1884	1330	53.5
14H30	1856	1330	57.8
15H00	1835	1330	62.0
15H30	1805	1330	66.0
16H00	1783	1330	69.7
16H30	1725	1330	73.3
17H00	1695	1330	76.4
17H30	----	----	79.3

Option 5:

LEVEL SENSOR READING:
HOLD-UP = 94.2%

Option 6PRESENT ERROR DISTRIBUTION:

FLOW = 0.0033
LIMIT = 0.0007
DF/DT = 0.0037

TOTAL = 0.0078

CYCLE NO. = 10
CALC. INT. = 26
NO. ADJUSTMENTS IN PRESENT CYCLE = 2

Option 7

MODULE	OUTFLOW RATES (L/S)	
	REQUESTED	ACTUAL
1	580	589
2	560	577
3	170	167

Option 8

* THE MACHINE TIME IS 15431
DO YOU WANT TO CHANGE TIME? Y/N
Y
* ENTER THE CORRECT TIME IN FORMAT HH MM(RETURN)
15 41

*** NO MORE RESPONSES REQUIRED ***

Option 9:

MODULE NO. 3 IS SET AT A FLOW
RATE OF 140 LITRES/SEC

* IS THE SETPOINT TO BE CHANGED? (Y/N)

Y

* ENTER THE NEW FLOW RATE SETTING FOR THIS MODULE
IN UNITS OF LITRES/SEC (E.G. 100(RETURN))

200

In addition to the requested output listed above, details concerning
the operation of the equalization tank over the preceding 24 hour
period are printed each day at 07h45 as follows:

ACTUAL RESULTS FOR LAST 24 HOURS

TIME	INFLOW L/S	OUTFLOW L/S			HOLDUP (%)
		MOD.1	MOD.2	MOD.3	
0800	1106	468	468	170	22.0
0830	1405	521	521	170	22.0
0900	1755	560	560	170	23.5
0930	1716	560	560	170	27.2
1000	1793	560	560	170	30.6
1030	1781	574	574	170	34.5
1100	1781	574	574	170	38.2
1130	1704	574	574	170	41.9
1200	1742	574	574	170	44.9
1230	1742	574	574	170	48.3
1300	1665	574	574	170	51.7
1330	1600	560	560	170	54.4
1400	1561	560	560	170	56.9
1430	1600	560	560	170	59.0
1500	1496	547	547	170	61.5
1530	1535	547	547	170	63.3
1600	1535	547	547	170	65.4
1630	1496	547	547	170	67.6
1700	1574	547	547	170	69.4
1730	1574	547	547	170	71.9
1800	1574	547	547	170	74.3
1830	1458	547	547	170	76.8
1900	1458	547	547	170	78.3
1930	1342	547	547	170	79.8
2000	1342	547	547	170	80.4
2030	1238	534	534	170	81.0
2100	1200	534	534	170	81.0
2130	1135	521	521	170	80.7
2200	1147	508	508	170	80.1

22H30	1147	508	508	170	79.8
23H00	1070	508	508	170	79.5
23H30	1070	508	508	170	78.6
0H00	1019	521	521	170	77.7
0H30	941	521	521	170	76.1
1H00	929	534	534	170	74.0
1H30	813	534	534	170	71.6
2H00	813	534	534	170	68.2
2H30	697	534	534	170	64.8
3H00	697	534	534	170	60.5
3H30	697	534	534	170	56.3
4H00	632	521	521	170	52.0
4H30	644	508	508	170	47.4
5H00	644	508	508	170	43.1
5H30	657	495	495	170	39.8
6H00	592	481	481	170	34.8
6H30	708	481	481	170	30.6
7H00	681	468	468	170	27.2
7H30	927	495	495	170	23.8

APPENDIX F

LIST OF PUBLICATIONS

This Appendix presents a list of papers which have been published or accepted for publication during the period in which the author was reading for the Ph.D degree. Only one of the papers deals specifically with the subject matter of this thesis i.e. the development of an equalization control strategy. The other two papers are concerned with the development and application of a general model for the activated sludge process; this being the major interest of the research group which includes the author.

The papers, published with the approval of the University of Cape Town and the Water Research Commission of South Africa, are the following:

1. Dold, P.L., Ekama, G.A. and Marais, G.v.R. (1979) "The Activated Sludge Process : Part I - A General Model for the Activated Sludge Process", Progress in Water Technology, 12, 47-77.
2. Dold, P.L., Buhr, H.O. and Marais, G.v.R. (1980) "A Computer-based Strategy for the Control of Equalization Tanks", Presented at the IAWPR Workshop on Practical Experience of Control and Automation in Wastewater Treatment and Water Resources Management, Munich and Rome, June 1980; to be published in Prog.Wat. Tech.
3. Van Haandel, A.C., Dold, P.L. and Marais, G.v.R. (1981) "Optimization of Nitrogen Removal in the Single Sludge Activated Sludge Process", To be presented at the IAWPR Eleventh International Conference, Cape Town, March 1982; to be published in Prog.Wat.Tech.